[redacted]

9
Z65·11548

Accessions No 15107

SID 62-557-3

Copy #1

QUARTERLY RELIABILITY STATUS REPORT (U)

NAS9-150

31 October 1962

4.5.4.7

ASPO DI[illegible] COPY
Destroy [illegible] longer in
Do not return to ASPO file

CLASSIFICATION CHANGE

To UNCLASSIFIED
By authority of GDS-EO 11652 Date 12/31/72
Changed by L. Shirley
Classified Document Master Control Station, NASA
Scientific and Technical Information Facility

[redacted]

~~This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18 U.S.C. Section 793 and 794. Its transmission or revelation of its contents in any manner to an unauthorized person is prohibited by law.~~

~~Downgraded at 3 year intervals; declassified after 12 years; DOD DIR 5200.10.~~

NORTH AMERICAN AVIATION, INC.
SPACE and INFORMATION SYSTEMS DIVISION

[redacted]

[redacted]

FOREWORD

The Quarterly Reliability Status Report is submitted in accordance with the Apollo documentation requirements delineated in NASA Contract NAS 9-150, Paragraph 4.5.4.7, of "Project Apollo Spacecraft Development Statement of Work," Part 4, dated 18 December 1961, and MIL-R-27542, Paragraph 5.4.3. The information contained herein covers the period from 1 August through 30 September 1962.

[redacted]

[redacted]

CONTENTS

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

ILLUSTRATIONS

Figure | Page

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

TABLES

INTRODUCTION

This document reports the significant reliability activities that occurred during the reporting period. Considerable effort was devoted to the analysis of subsystems; this report includes failure-mode analyses, component-reliability allocations, and logic network diagrams.

Another important area reported, which will become more significant in future reports, is that of system and subsystem testing. As a result of cost reduction and schedule adjustments, considerable curtailment of the previously proposed system and boilerplate tests has occurred. However, developmental testing of some components and equipment has begun, and these tests are discussed in the text.

Other efforts that are rapidly gaining impetus are discussed in subsequent sections. These include data operations, reliability education, component technology, and supplier surveys.

The final sections of this document report programmed activities. Some of these are newly in progress; others are continuing functions.

I. RELIABILITY PROGRAM IMPLEMENTATION

RELIABILITY PROGRAM PLAN

DEFINITION

The Reliability Program Plan delineates the responsibilities of the Apollo reliability organization; it also delineates the implementation and surveillance of the Apollo reliability and crew safety program and the qualification-reliability test plan. This effort includes the following:

Establishment of reliability requirements and criteria

Establishment of the reliability crew-safety objectives

Development and maintenance of data- and failure-reporting systems

Review and analysis of designs

Establishment and implementation of reliability indoctrination and training programs

Support of ground and flight operations

Definition and control of subcontractor reliability programs

Preparation of reports and contributions in support of contractual documentation requirements

Establishment of schedules for the accomplishment, control, and audit of reliability activities

STATUS

Verbal approval was given to the Reliability Program Plan (SID 62-203) at a meeting held September 27 and 28 at MSC Houston. Minor changes are planned for the next revision of the plan scheduled for January 1963.

QUALIFICATION-RELIABILITY TEST PLAN

DESCRIPTION

The Qualification-Reliability Test Plan describes the methods to be employed by S&ID and all Apollo subcontractors and suppliers to qualify hardware for spacecraft usage. The objective of the test plan is to utilize, to the maximum, data from all test areas. Information will be obtained from qualification, reliability, ground, spacecraft, acceptance, prelaunch, launch, flight, and postflight tests. This information will be evaluated qualitatively and quantitatively for qualification and reliability demonstration purposes. Continuity of test data from lower levels of assembly to tests on the complete spacecraft and on ground support equipment will be maintained throughout the program.

TEST PLANNING OBJECTIVES

The primary purpose of the qualification-reliability tests is to obtain information useful for verifying stability and integrity of the equipment design. The ultimate objective is to demonstrate the achieved levels of reliability at specific confidence levels to the highest degree possible. Achievement of this objective can be substantially realized through qualifications tests that are designed to assure that the equipment is capable of successfully completing the lunar-landing and earth-return missions, as required.

On 26 June 1962, a briefing on the revised Qualification-Reliability Test Plan (SID 62-204) was presented to NASA Reliability personnel from headquarters, Washington D. C.; Manned Spacecraft Center, Houston; and Marshall Space Flight Center, Huntsville, Alabama. The purpose of the briefing was to outline the concept and to discuss the rough draft of the revised plan. The new plan places greater emphasis on mission simulation, parameter variability, and off-limit testing than the previous editions of this document did. NASA concurred with the approaches presented and requested that S&ID submit the final document on 23 July 1962, in accordance with previous agreements.

TEST PLAN STATUS

Manned Spacecraft Center reliability personnel gave verbal approval of the document at a meeting in Houston on 27 and 28 September 1962. A letter containing formal approval is expected soon.

[redacted]

HARDWARE UTILIZATION REVIEW

Apollo reliability engineering reviewed all test programs planned for spacecraft hardware in order to provide a new estimate of the number of qualification-and-reliability test articles required to demonstrate reliability. Each test program (development, boilerplate, and spacecraft) was evaluated to determine the amount of useful data that will be obtained for reliability demonstration. A comparison between these data and the number of test hours required to demonstrate reliability was made to provide the estimate of the number of test articles required. (NASA and S&ID agreed to use the spacecraft level of reliability, 0.96 at 90-percent confidence level, as a minimum demonstration objective for each subsystem.) The hardware utilization list was revised in accordance with these requirements and presented to NASA for review in September. No changes were requested by NASA.

TEST ACCOUNTING SYSTEM

A test record book is being prepared for each subsystem and the associated GSE as an aid to implementing the test accounting system. The purposes of this internal document, and the accounting system, are to maintain an accurate history of the tests performed on each subsystem and to provide adequate information with which to assess the applicability of each test to the reliability demonstration program. The book will contain schedules of all tests planned, including development, so that reliability engineering can plan to witness significant environmental and off-limit tests. At various stages of completion, the record book will contain the following information:

System description

Reliability apportionment and prediction

Failure-mode, cause-and-effect analysis

Test schedules

Pretest analysis

Qualification-and-reliability test procedures

Running test status and analyses

Test data and results

Final test reports

[redacted]

TEST PLANNING GUIDANCE

The qualification-reliability test group, in conjunction with the S&ID reliability training group, are in the process of preparing a test planning guide that will be used by all Apollo engineers involved in the preparation of procurement specifications. The intent of the document is, first of all, to insure uniformity as well as completeness and accuracy of testing; and what is probably more important, to effect cross-pollination of ideas and talents within S&ID, thereby, generating the most effective utilization of available capabilities. The document will contain the following information and will probably be the most complete guide to reliability test planning available.

The effects of qualification-reliability test program controlling documents and their application specifically to Apollo concepts.

Methodology for allocating a fixed amount of dollars for reliability testing of a non-homogeneous system or subsystem to assure optimum utilization of the test data.

Methodology for test planning to determine the distribution-of-strength and stress-strength margins.

Techniques for obtaining high confidence from "small" test sample sizes by preplanning an integrated program.

Application of accelerated reliability testing.

COMMERCIAL TESTING LABORATORY EVALUATION

Apollo-Saturn S-II Coordination

Apollo reliability is coordinating with Saturn S-II reliability a mutual program for commercial-test-laboratory evaluations. To date, a list of 70 test laboratories throughout the United States has been prepared. Letters requesting information about their facilities, capabilities, and test background are being sent to each laboratory. A mutual file of information concerning test laboratory facilities is being set up for reference. The information will be analyzed, and a system for laboratory surveys and certifications will be activated, based on test capabilities and geographical location. Effort is being made to coordinate efforts between Apollo and Saturn S-II reliability groups to eliminate any duplication of efforts.

[redacted]

Subcontractor Facility Survey

In addition to the above exercise, a more detailed survey of all the S&ID subcontractor facilities is underway. The purpose of this is three-fold. Survey data will form a baseline from which all test requirements and capabilities may be referenced, it will facilitate the determination of requirements for additional facilities at subcontractor plants, and it will provide the data required to determine where and by whom the relevant test should be performed. A complication in this study is the effect of scheduling and other program commitments.

QUALIFICATION STATUS REPORT

The first revision of the Qualification Status Report (SID 62-784) was completed and submitted to NASA. The revision presented updated information of the status of qualification testing and was not a change in the format of the document.

II. SUBSYSTEM ANALYSIS ACTIVITY

ELECTRONIC

RELIABILITY PREDICTIONS

Part Failure-Rate Estimates

A study was made to determine the relative reliabilities of parts comprising the equipment of the spacecraft electronics subsystems. From a breakdown by class, the parts were identified according to two basic categories. The first category consisted of parts that conformed to Minuteman standards or their equivalent. The second consisted of parts that were specified for use by contractors and subcontractors. From this breakdown, a comparative index was formulated by which the relative reliabilities of equipment using the Minuteman-or-equivalent parts were contrasted to those of equipment using contractor-specified parts. This study showed, for example, that a reduction by an order of magnitude for guidance-and-navigation-equipment failure rates is possible through the use of Minuteman-equivalent parts. Results of this study are given in Table 1.

Equipment Reliability Estimates

Equipment reliability estimates were made for the spacecraft electronic subsystems, based on a state-of-the-art reliability index. The state-of-the-art index was obtained from equipment reliability values calculated from part-failure rates based on Minuteman standards or equivalent. In cases for which Minuteman-standards were not applicable, the highest-reliability parts available were used. The electronic-equipment reliability estimates thus obtained were formulated into a Monte Carlo computer program designed to evaluate the overall spacecraft mission-success and crew-safety reliability estimates for each mission phase of a 336-hour lunar orbital rendezvous mission, as well as for the completed mission, neglecting lunar excursion module equipment. This computer program was designed with the potential of evaluating 20,000 simulated missions having varying parameters. It is anticipated that the results of the first run of this Monte Carlo computer program will give an estimate of the overall spacecraft-reliability and crew-safety probability. Refined results will be obtained as more information becomes available.

Table 1. Spacecraft Electronics Part Failure Rates

Part	Apollo Generic	Advanced Polaris	
	Equivalent Minuteman Standards	Mark II Bench Standards	Mark II Generic Standards
Capacitor	0.014	Tantalum 4.38000 Ceramic 0.03925	4.380 0.070
Resistor	0.0044	0.0157	0.210
Diode	0.015	0.0155	0.199
Transistor	0.063	0.2870	0.333
Transformer	0.03	1.0000	2.200
Inductor	0.06	2.2000	2.200
Crystal	0.06	0.1000	0.100
Note: Failure rates are x 10^{-6} hours.			

COMPONENT AND EQUIPMENT ANALYSIS

Summation Indices of Part-Failure Rates by Classes

All available pertinent data were used to establish summation indices of part-failure rates by classes for all of the equipment of the spacecraft electronic subsystems in support of an overall parts-improvement program. Tabulations were made by classes of the total number of parts, the part generic failure rates, the product of the number of parts and the summation of the mission-phase operating times, and the product of these three. This summation index gives an indication of estimated part failures by classes per million missions. The tabulated results of this study are shown in Table 2. A computer program is being run to determine the percentage of mission failures caused by each class of electronic subsystem parts.

[redacted]

Table 2. Electronic Subsystems - Part Failure Rates by Classes

Part	Number (N)	Generic Failure Rate (x 10^{-6})	Number of Parts x Mission Phase Operating Times (Nt)	Failures per Million Missions (Nt) (10^{-6})
Transistor	8,823	0.063	1,015,700	63,989
Diode	14,165	0.015	2,160,300	32,405
Capacitor	6,575	0.014	801,850	11,226
Resistor	16,153	0.0044	2,162,500	9,515
Tube	9	3.0	294	882
Transformer	235	0.03	52,551	1,577
Inductor	182	0.06	21,460	1,288
Crystal	10	0.06	929	56
Connector	416	0.50	92,500	46,250
Relay	109	2.5	31,694	79,235
Varactor	10	0.01	1,000	10
Switch	56	0.14	12,803	1,782
Sensor	226	0.016	75,916	1,215
Band-pass filter	23	0.08	3,111	249
Memory core	17,140	0.0001	754,500	75
Potentiometer	147	0.26	42,659	11,091
Heater coil	6	0.2	1,026	205
Accelerometer	4	50.0	414	20,700
Meter	8	1.38	2,690	3,712
Prism, lens	2	0.06	77	5
Mirror	2	0.005	76	
Servo motor	8	20.0	1,468	29,360
Drive motor	10	20.0	297	5,940
Gyro	8	50.0	24,060	1,203,000
Synchro motor	11	20.0	3,025	60,500
Lamp	48	8.0	1,613	12,904
U-joint	2	0.4	124	50
Dust seal	1	3.0	62	186
Circuit breaker	8	2.5	336	840
Cam follower	1	3.0	62	186
Ball bearing	4	0.3	247	74
Gear	10	0.3	1,202	361
Encoder and servo tachometer	3	40.0	78	3,120
Servo torquer	13	20.0	2,849	56,980
Gear tooth counter	4	0.09	116	10
Telescope	1	11.6	38	441
Size 16 pulse pendulum	3	50.0	78	3,900
Bearing	3	0.3	1,008	302
Slip ring	11	2.0	285	570
Gas generator	1	3.33	30	100
Thermistor	1	0.10	336	34
Thermostat	4	6.0	104	624
Size 25 inertial rate integrating gyro	3	200.0	78	15,600
Totals	64,725		7,271,506	1,680,549

[redacted]

Logic Networks

Related functions of equipment in the guidance and navigation, stabilization and control, and communications and data subsystems were studied, and reliability logic networks depicting these relationships were developed.

The purpose of these networks is to provide a basis for making reliability predictions and apportionments, to determine the need for on-board spares and in-flight tests, to support the emergency-detection systems analysis, and to define the required crew action based upon abort criteria. The networks show the general functional relationship of equipment of the spacecraft electronic subsystems that are essential to mission success and crew safety for each successive phase of the lunar orbital rendezvous mission. It is understood that modification in the logical relationships will have to be made to conform to information of more specific and detailed nature as analysis of the system is expanded. Figure 1, and Figure 2, sheets 7, 8, 9, and 10, show the relationship of the equipment that will have to operate with the probability of successfully completing all stages of the mission to meet the requirements of mission success. These stages of the mission include the phases from launch through the translunar and lunar orbital phases, and the lunar landing, in which equipment failures do not occur that would necessitate an abort or modification of the mission; they also include a successful return to earth without additional failures that would cause loss of the spacecraft or crew.

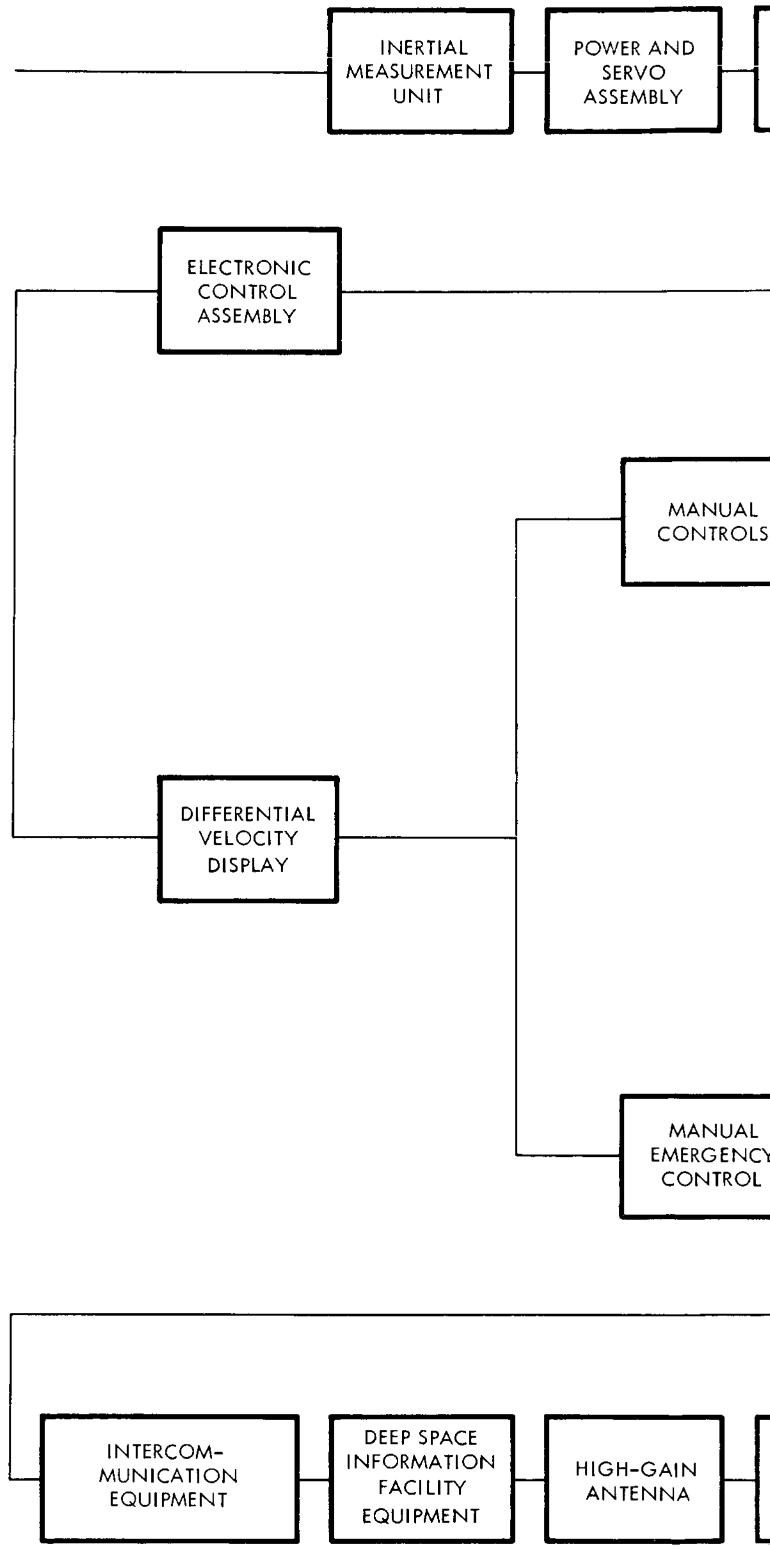
Figure 1 (Mission Success from Launch to Lunar Excursion Module Launch) shows the relationship of the equipment that establishes the criteria for abort according to the rule that the mission will be discontinued and the spacecraft returned to the earth when failures have occurred such that one additional failure would cause loss of the spacecraft and crew. It is recognized that these criteria must be evaluated for each condition to assure that it produces the proper balance between crew safety and mission success; in addition, considerations must be taken into account to allow operations in deferred abort modes pending transitions to later mission phases.

Figure 2, sheets 1 through 10, shows the relationship of the equipment that will necessarily operate in such manner that all redundancies, alternate modes, and equipment-availability factors would have to be used to assure the highest probability of success. This equipment must satisfy the following crew-safety requirement: The probability of mission success, plus the product of the probability that an abort will occur times the probability that the abort would result in safe recovery of the crew, must equal or exceed the required reliability value.

Table 3 delineates the abort criteria by listing the equipment whose failure would necessitate a mission abort.

[redacted]

#1



INERTIAL MEASUREMENT UNIT
POWER AND SERVO ASSEMBLY
ELECTRONIC CONTROL ASSEMBLY
MANUAL CONTROLS
DIFFERENTIAL VELOCITY DISPLAY
MANUAL EMERGENCY CONTROL
INTERCOM- MUNICATION EQUIPMENT
DEEP SPACE INFORMATION FACILITY EQUIPMENT
HIGH-GAIN ANTENNA

#2

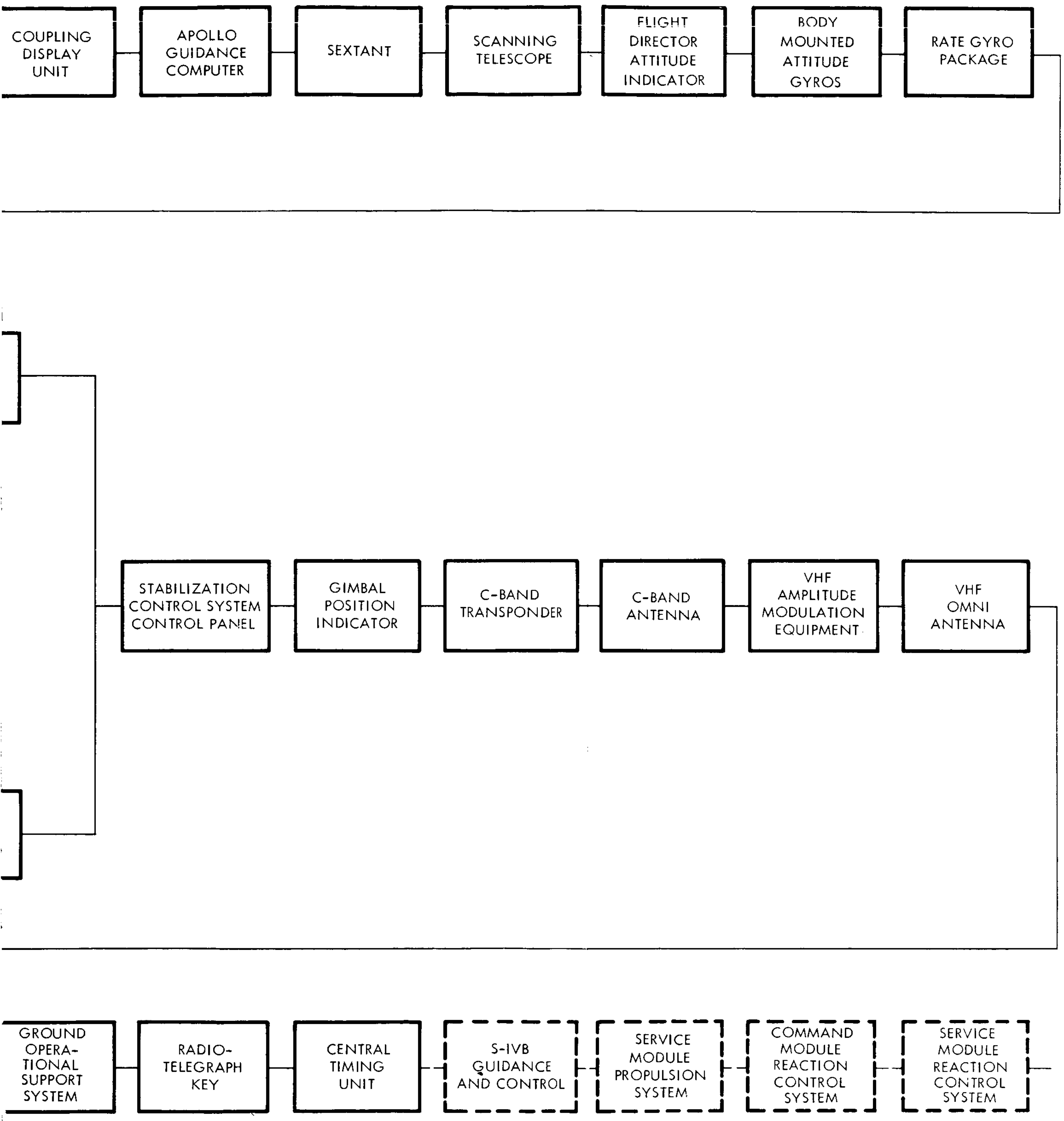


Figure 1. Logic Network, Launch to Lunar Excursion Module Launch

[redacted]

Sheet 1. Launch to ≈ 100, 000 Feet

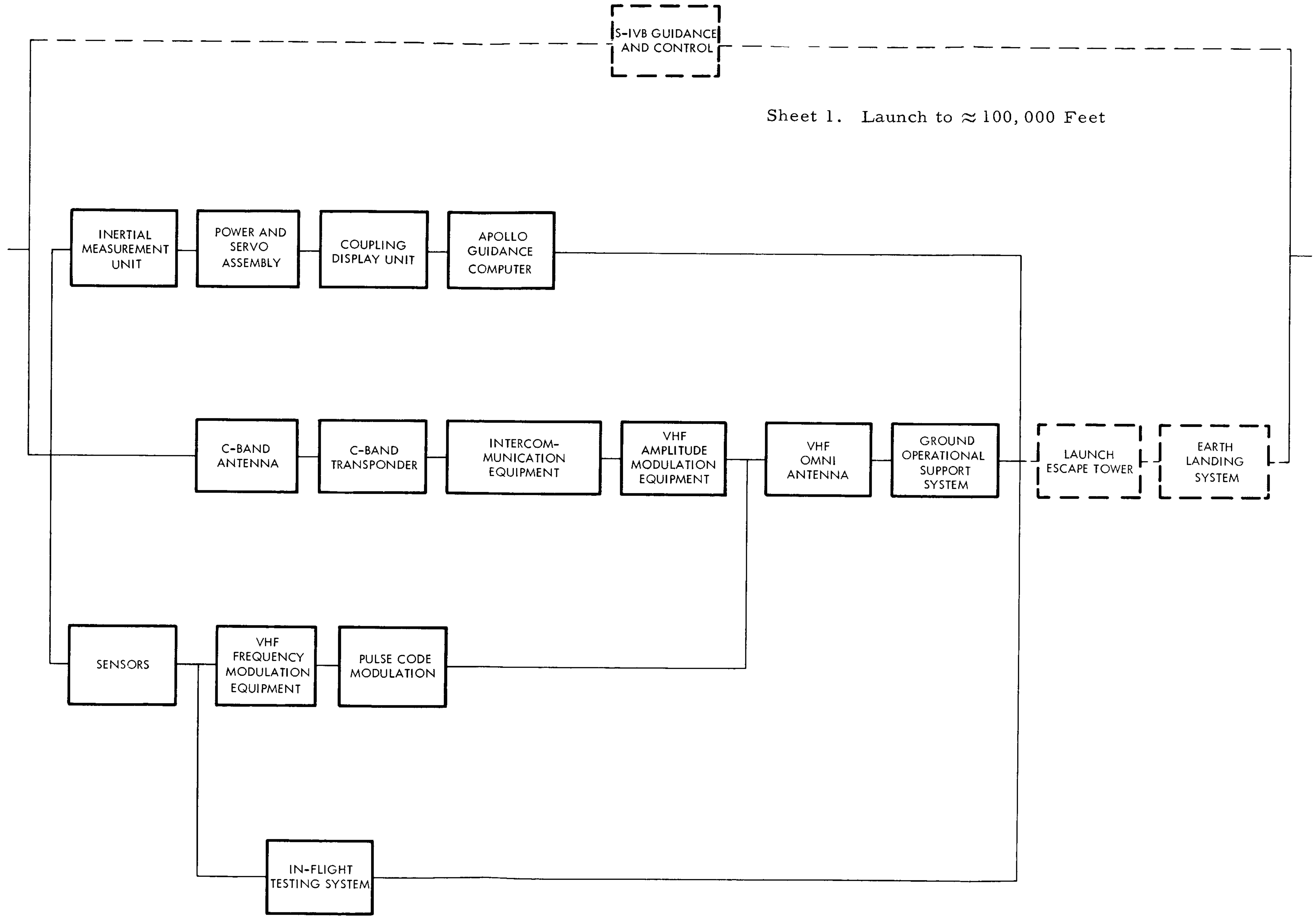


Figure 2. Crew Safety and Mission Success Logic Network

[redacted]

~~CONFIDENTIAL~~

Sheet 4. Earth Orbit to Translunar Coast (Cisearth)

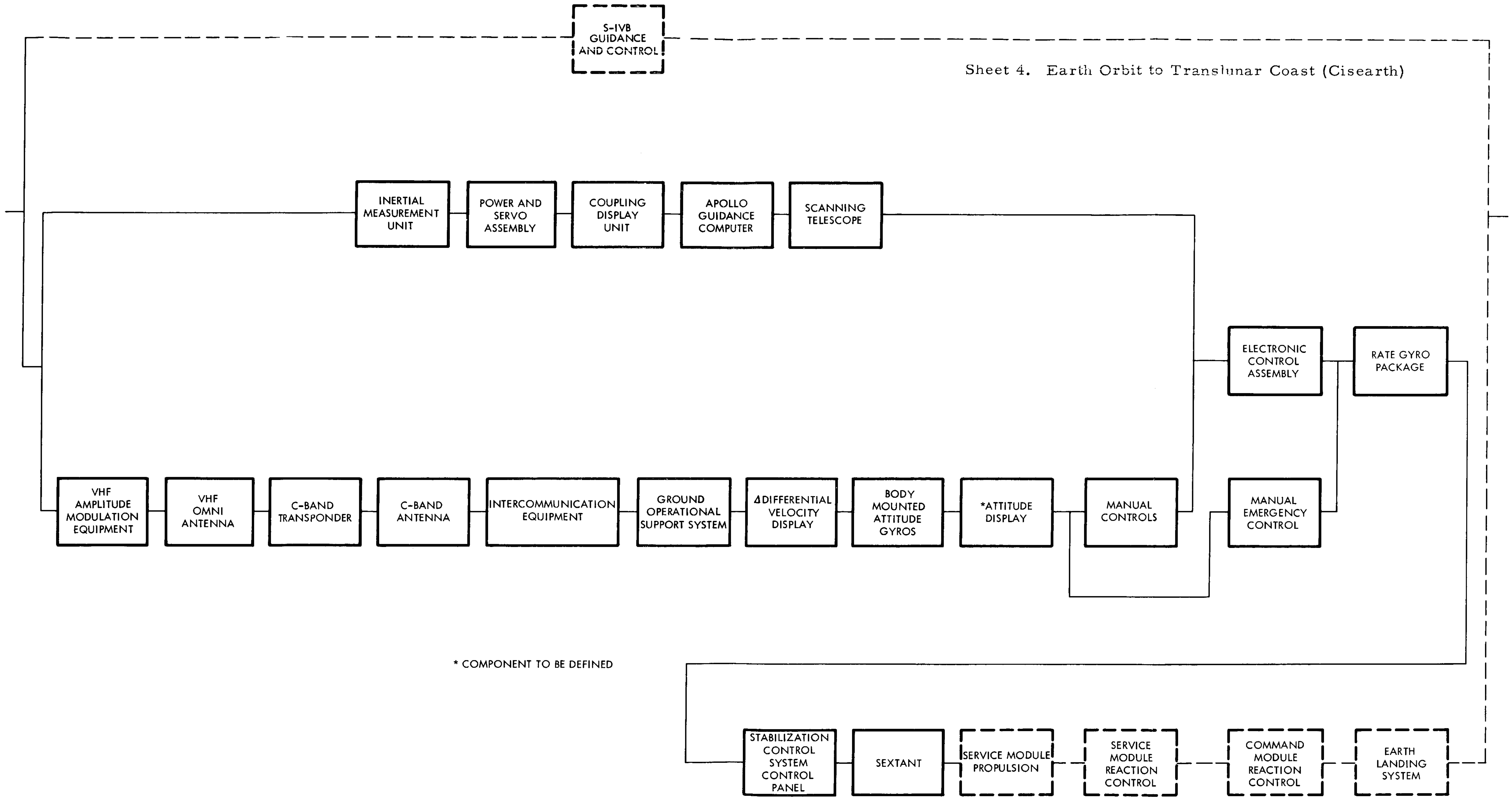
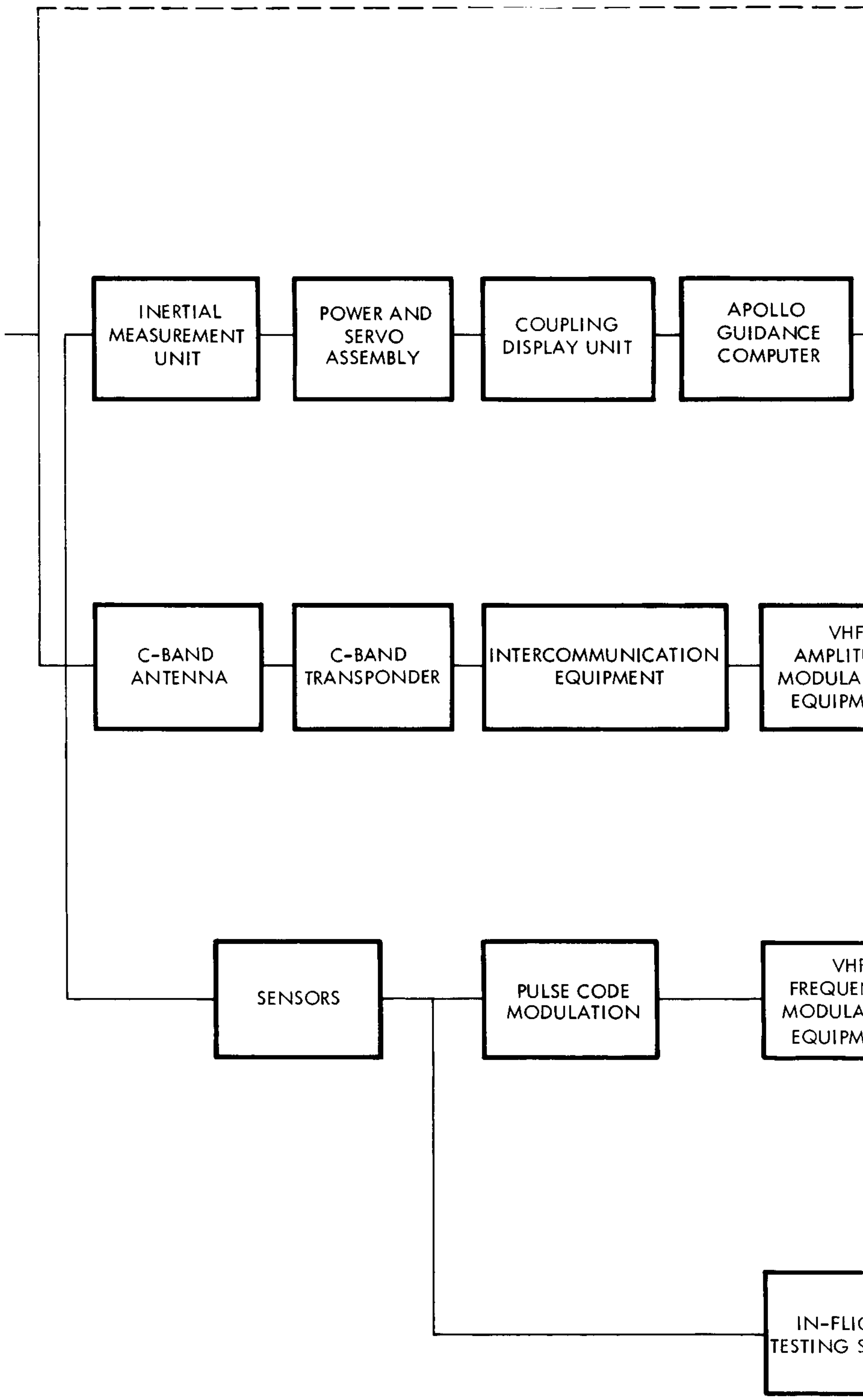


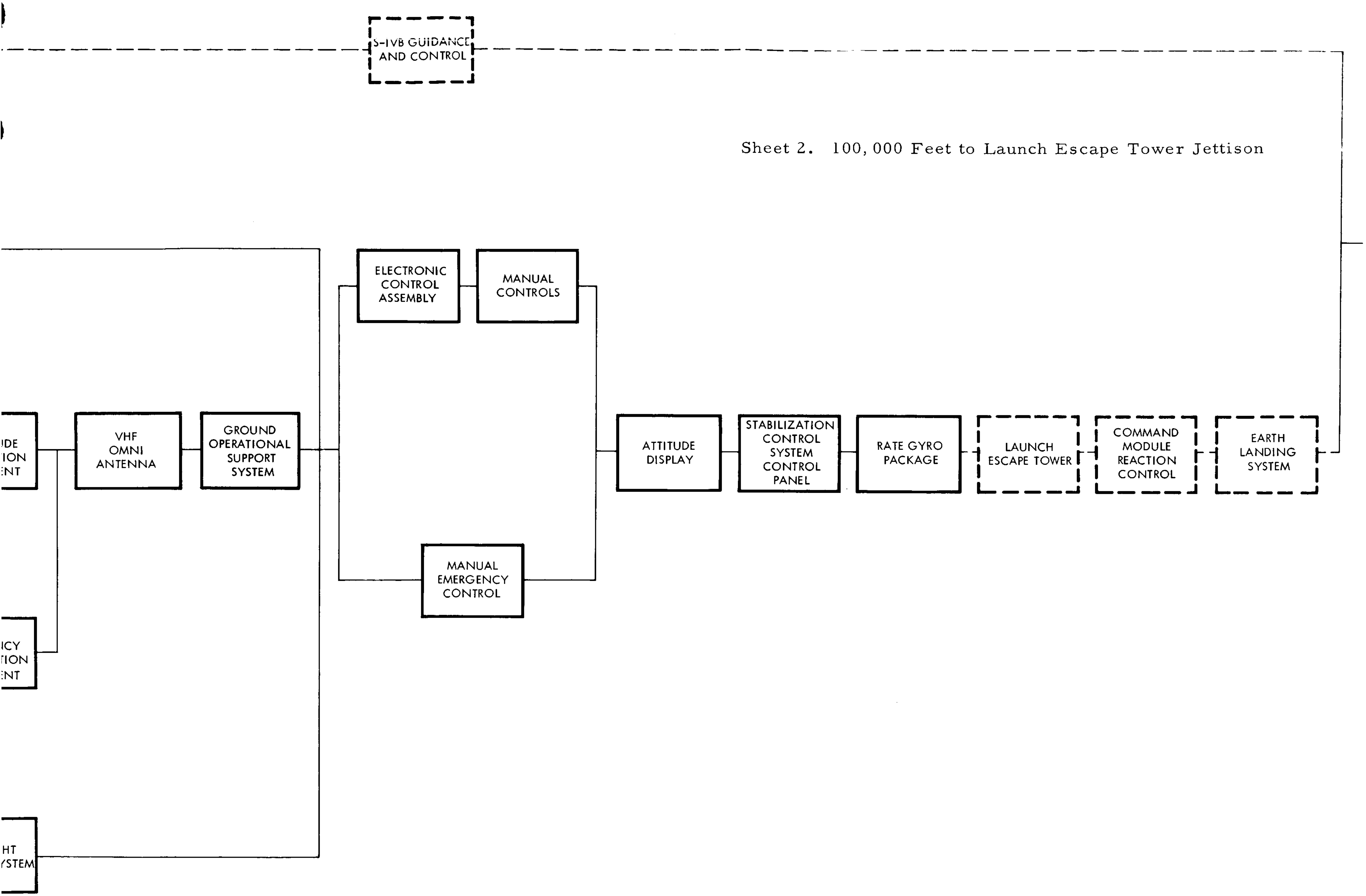
Figure 2. Crew Safety and Mission Success Logic Network

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~



1

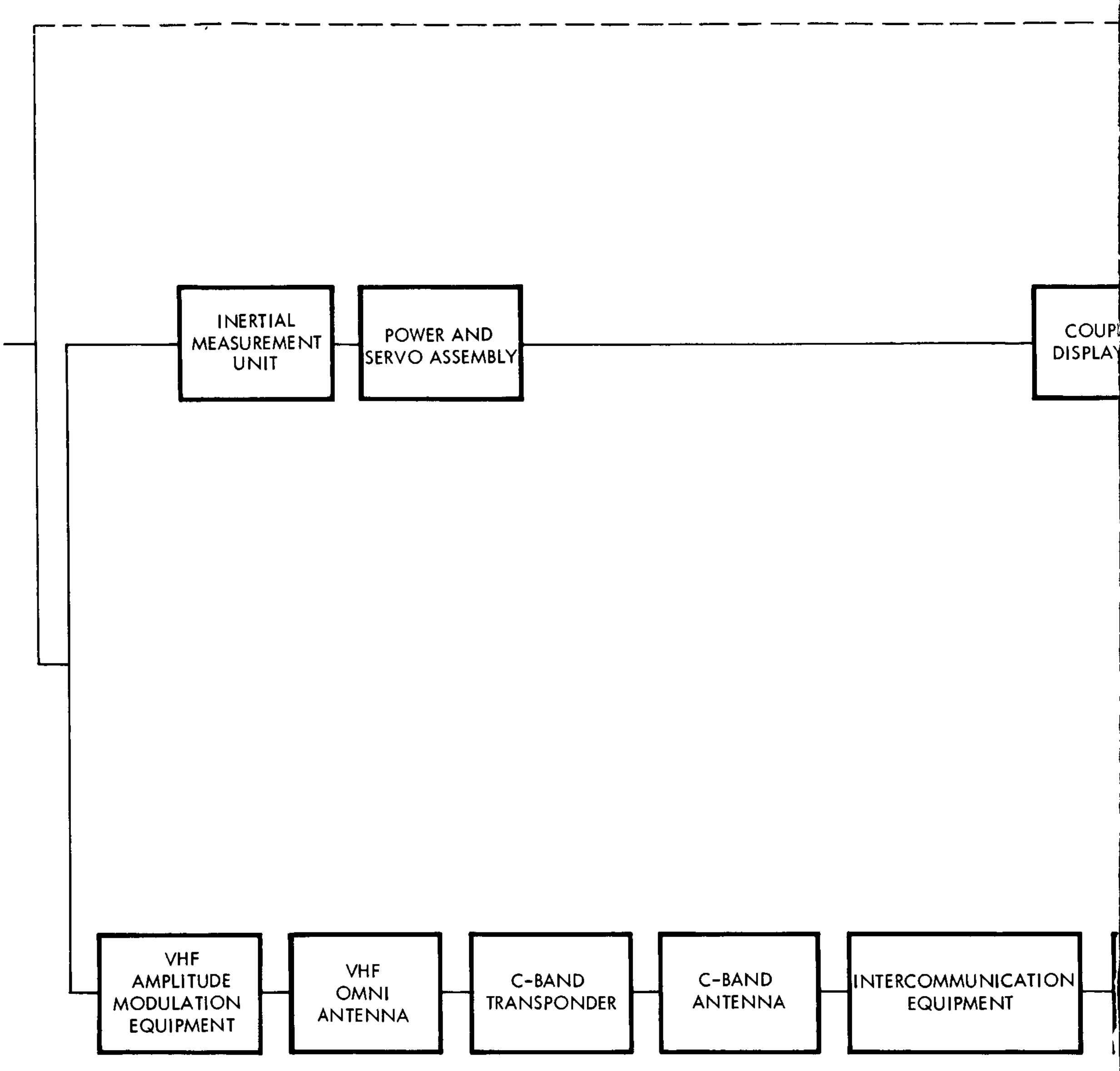


2

Figure 2. Crew Safety and Mission Success Logic Network

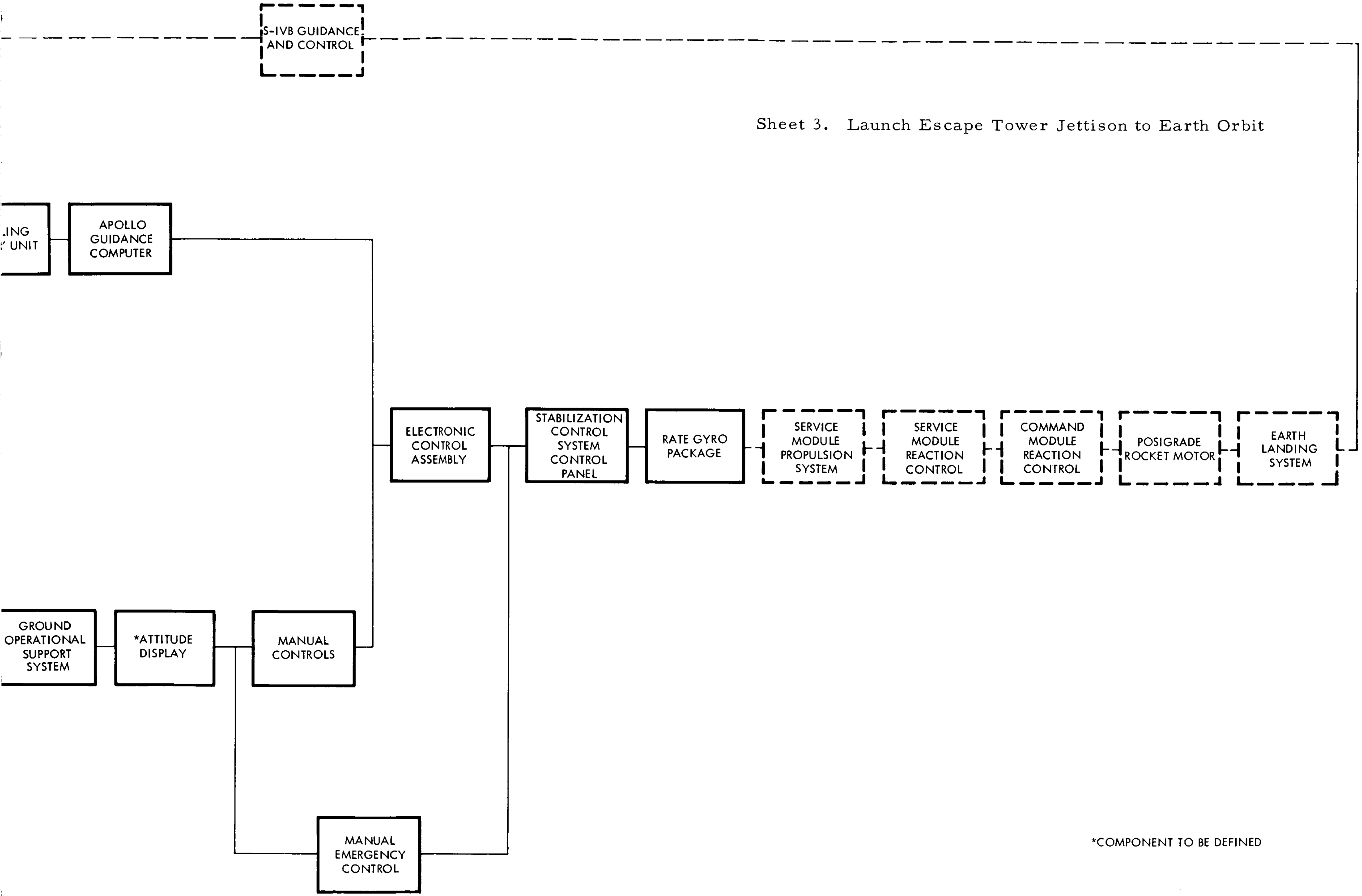
~~CONFIDENTIAL~~

[redacted]



INERTIAL MEASUREMENT UNIT
POWER AND SERVO ASSEMBLY
VHF AMPLITUDE MODULATION EQUIPMENT
VHF OMNI ANTENNA
C-BAND TRANSPONDER
C-BAND ANTENNA
INTERCOMMUNICATION EQUIPMENT

Sheet 3. Launch Escape Tower Jettison to Earth Orbit

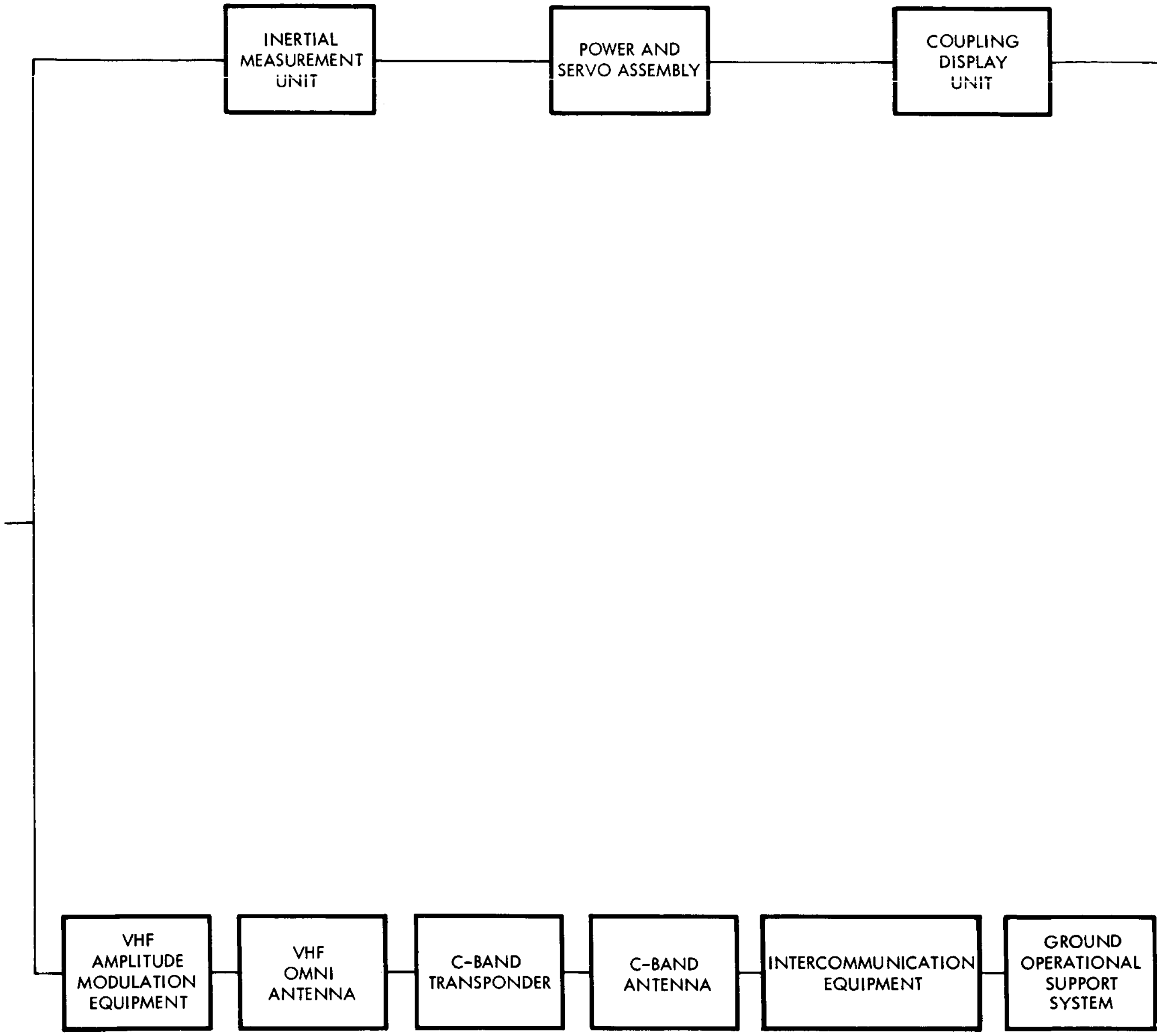


*COMPONENT TO BE DEFINED

3

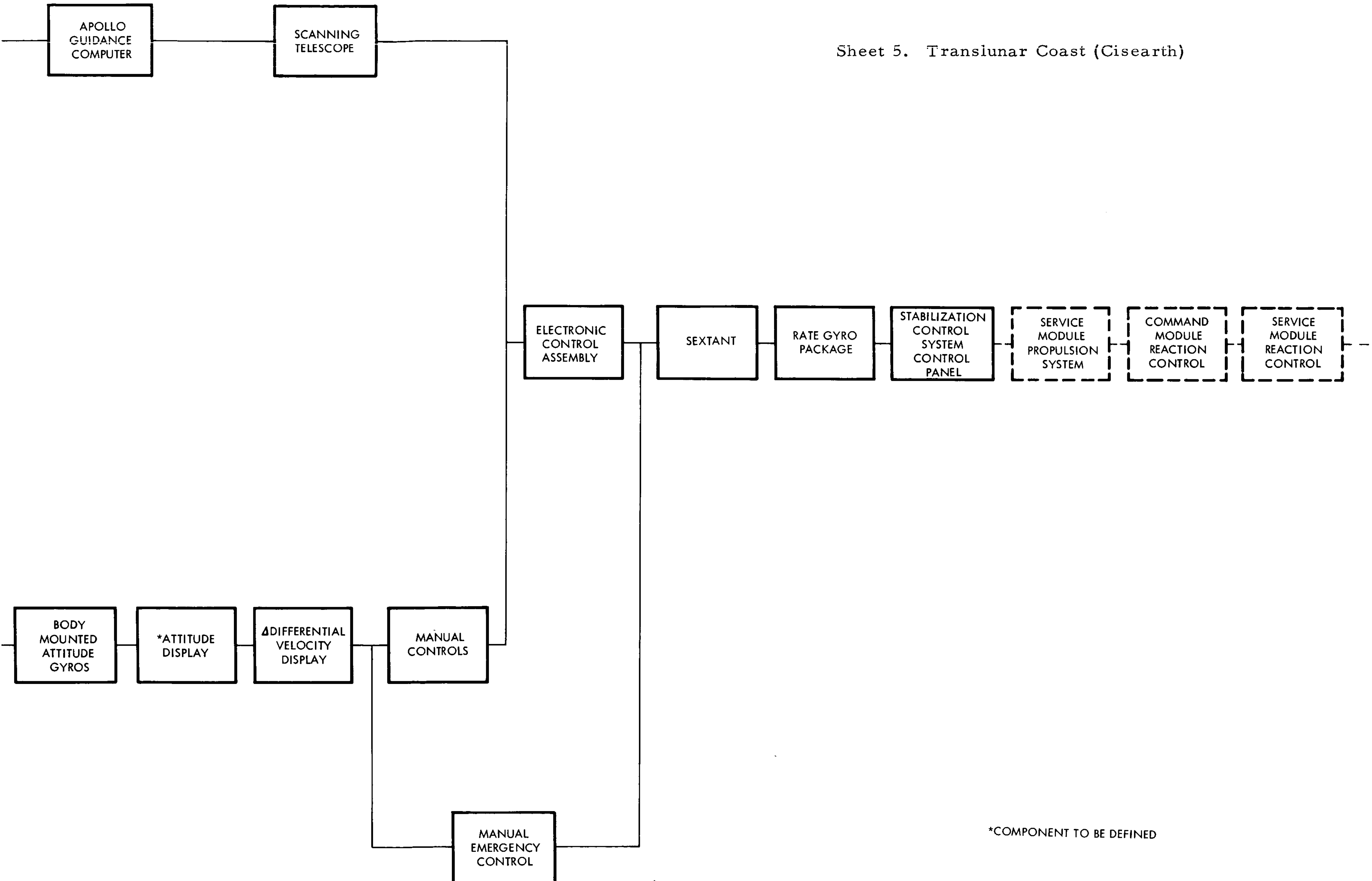
Figure 2. Crew Safety and Mission Success Logic Network

[redacted]



INERTIAL MEASUREMENT UNIT
POWER AND SERVO ASSEMBLY
COUPLING DISPLAY UNIT
VHF AMPLITUDE MODULATION EQUIPMENT
VHF OMNI ANTENNA
C-BAND TRANSPONDER
C-BAND ANTENNA
INTERCOMMUNICATION EQUIPMENT
GROUND OPERATIONAL SUPPORT SYSTEM

Sheet 5. Translunar Coast (Cisearth)

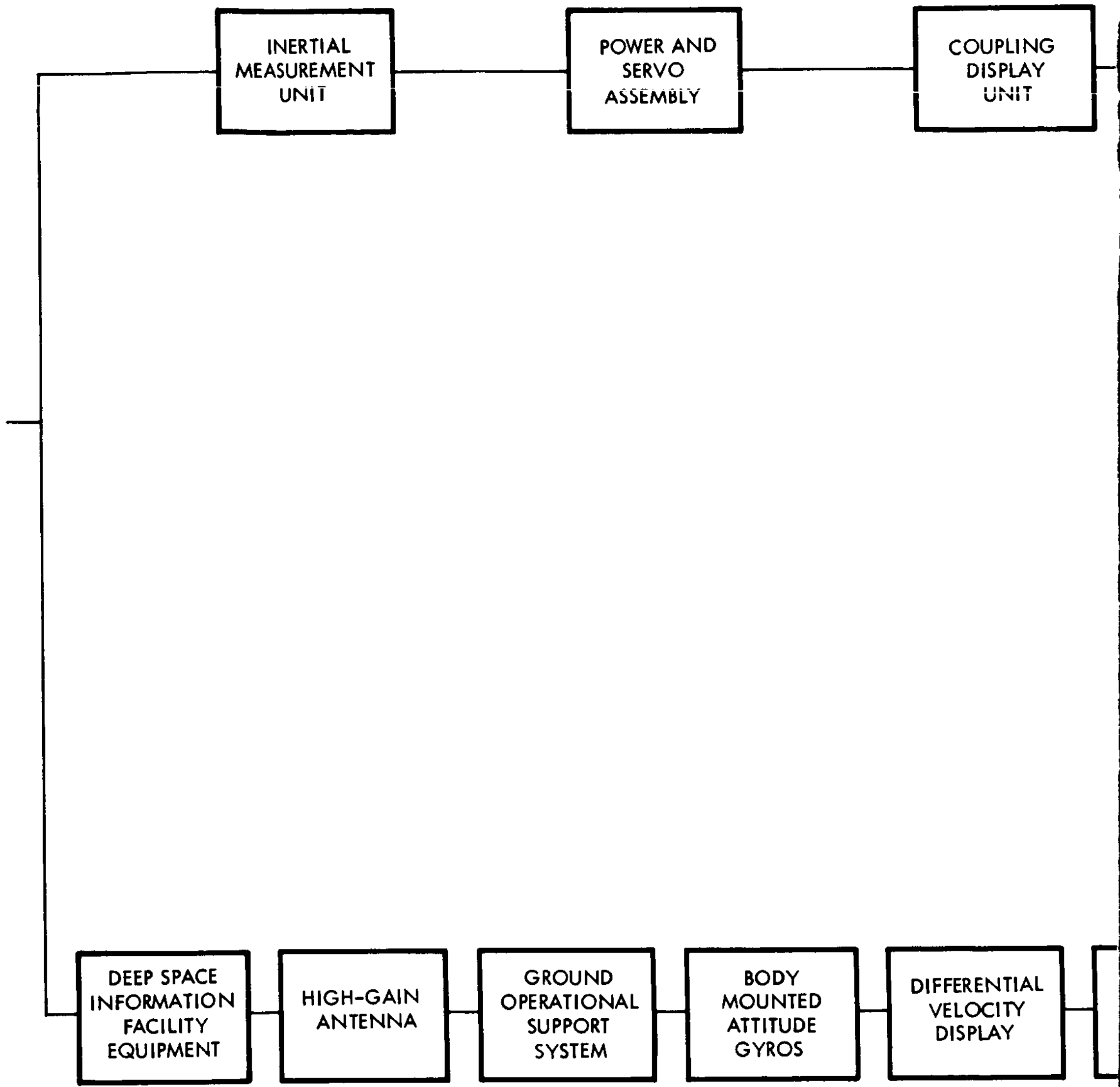


2

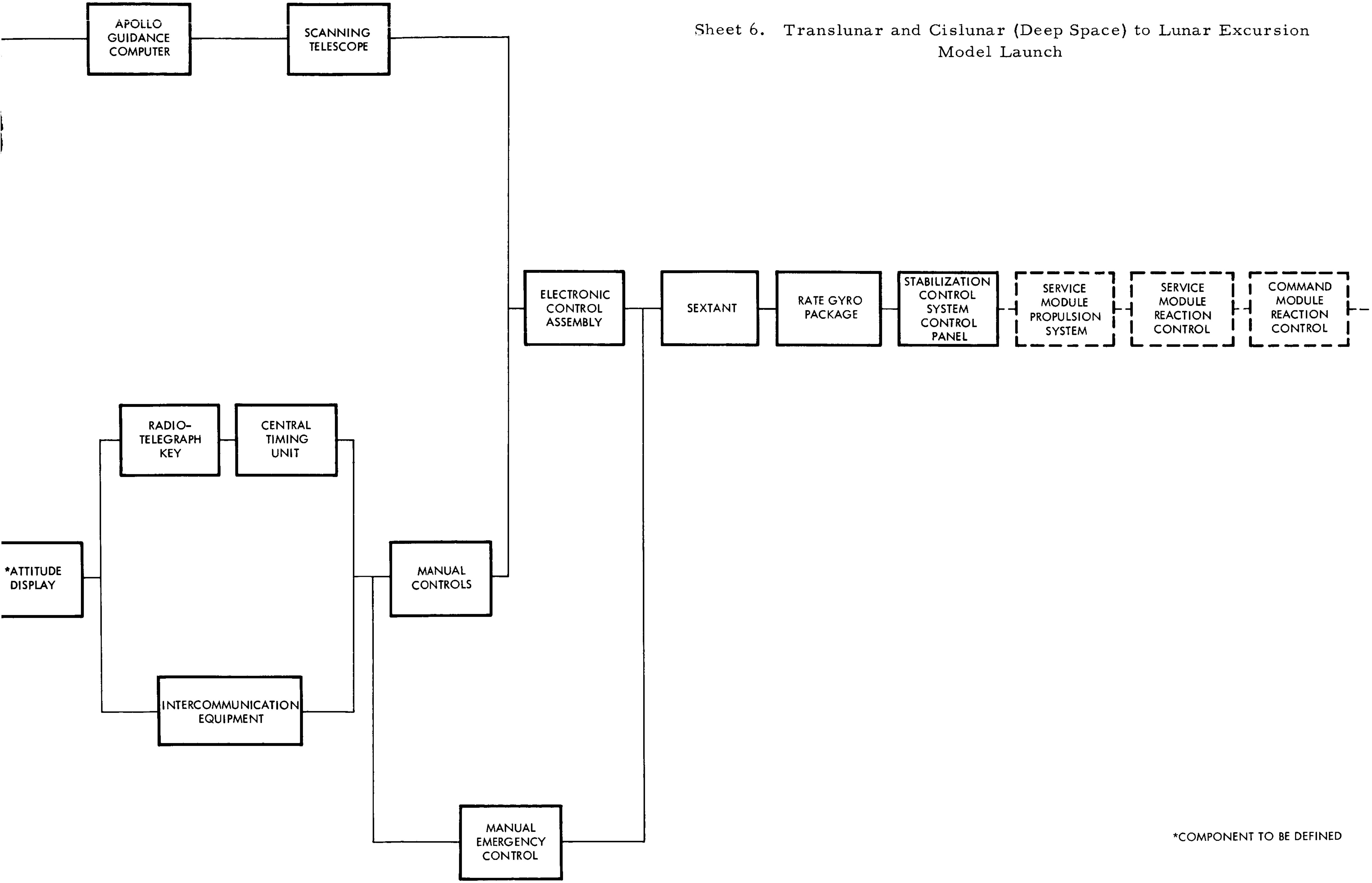
Figure 2. Crew Safety and Mission Success Logic Network

[redacted]

~~CONFIDENTIAL~~



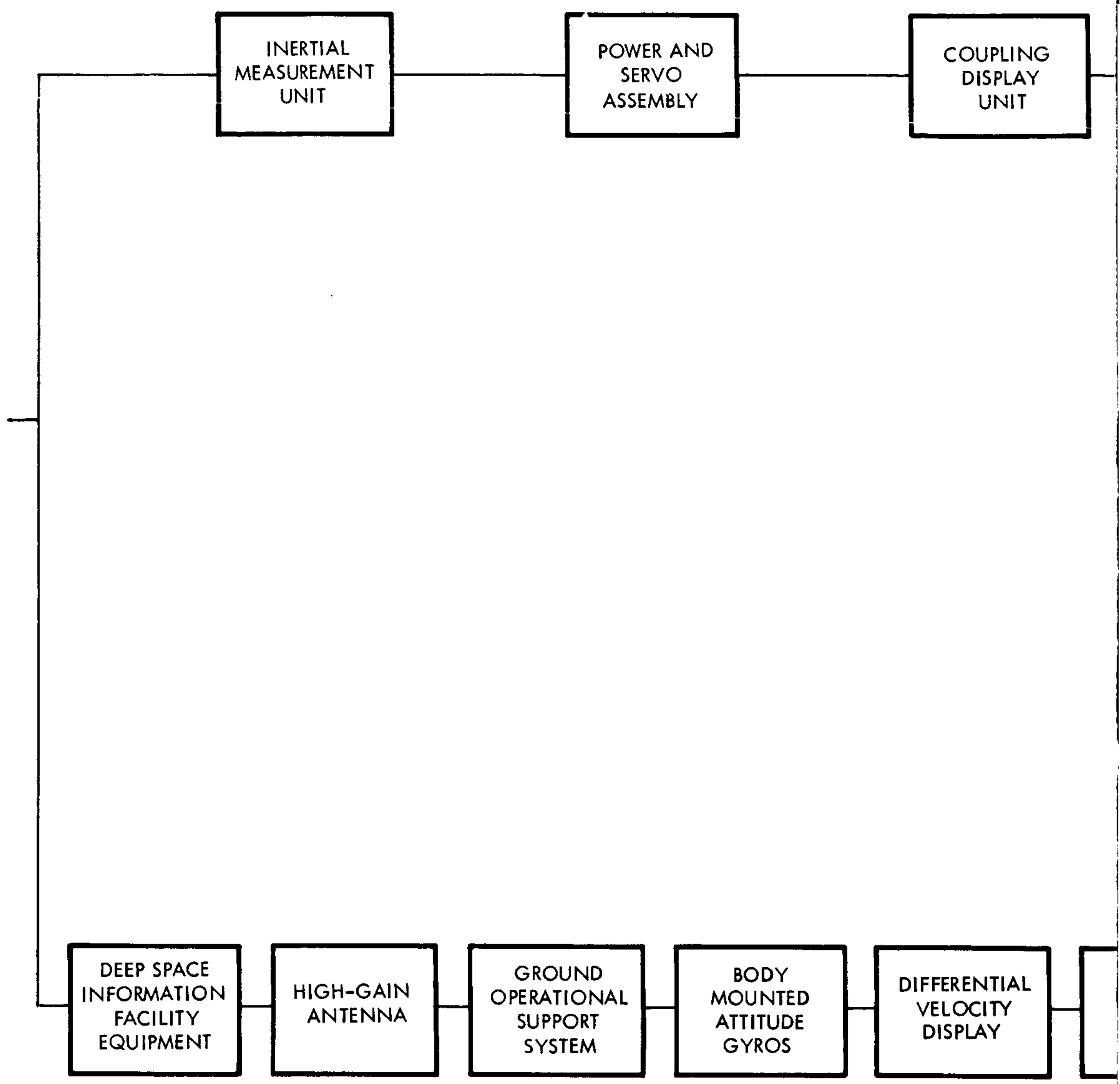
Sheet 6. Translunar and Cislunar (Deep Space) to Lunar Excursion Model Launch



2

Figure 2. Crew Safety and Mission Success Logic Network

[redacted]


INERTIAL MEASUREMENT UNIT
POWER AND SERVO ASSEMBLY
COUPLING DISPLAY UNIT
DEEP SPACE INFORMATION FACILITY EQUIPMENT
HIGH-GAIN ANTENNA
GROUND OPERATIONAL SUPPORT SYSTEM
BODY MOUNTED ATTITUDE GYROS
DIFFERENTIAL VELOCITY DISPLAY

Sheet 7. Lunar Excursion Model Launch Through Transearth (Deep Space)

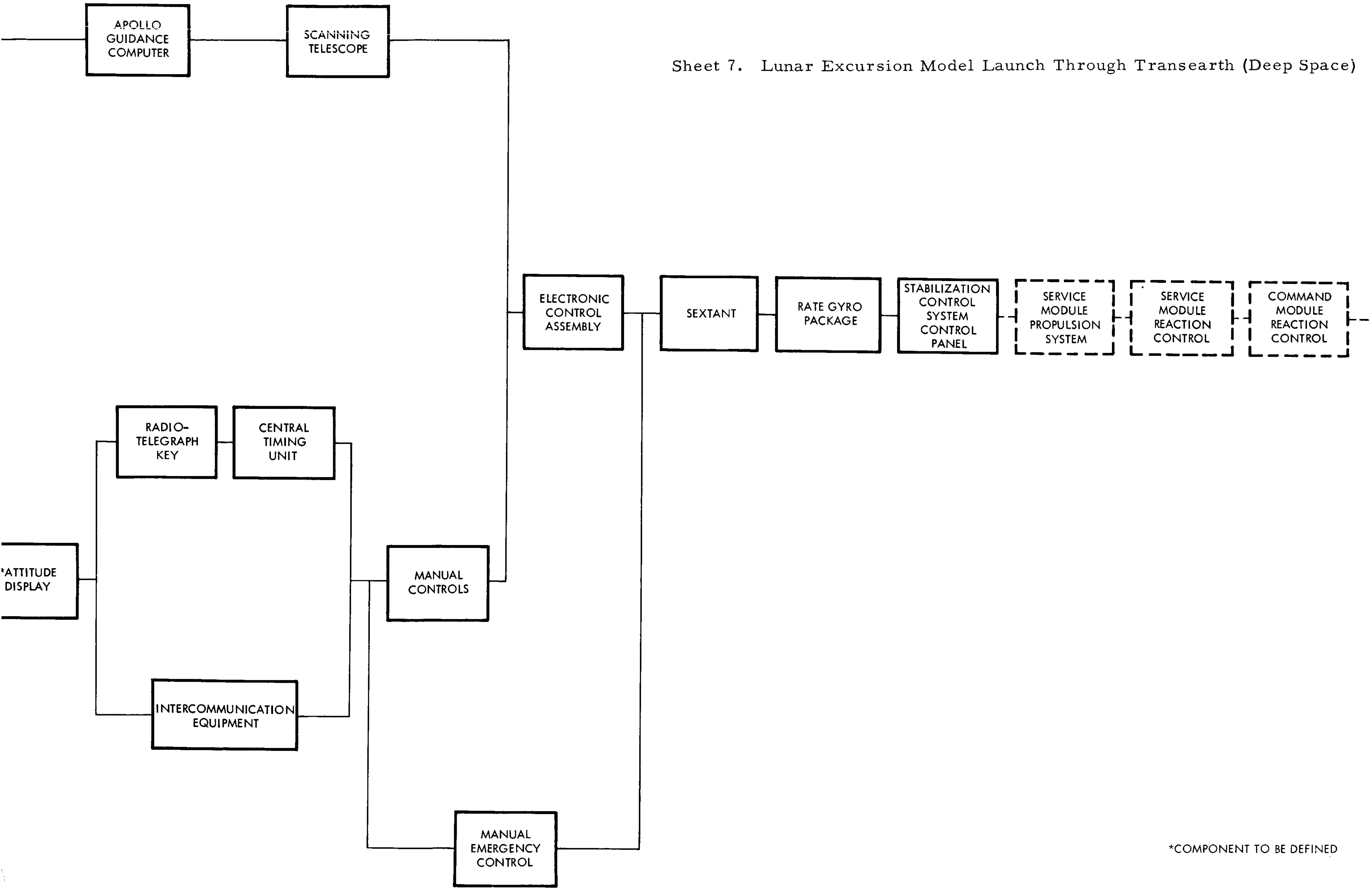
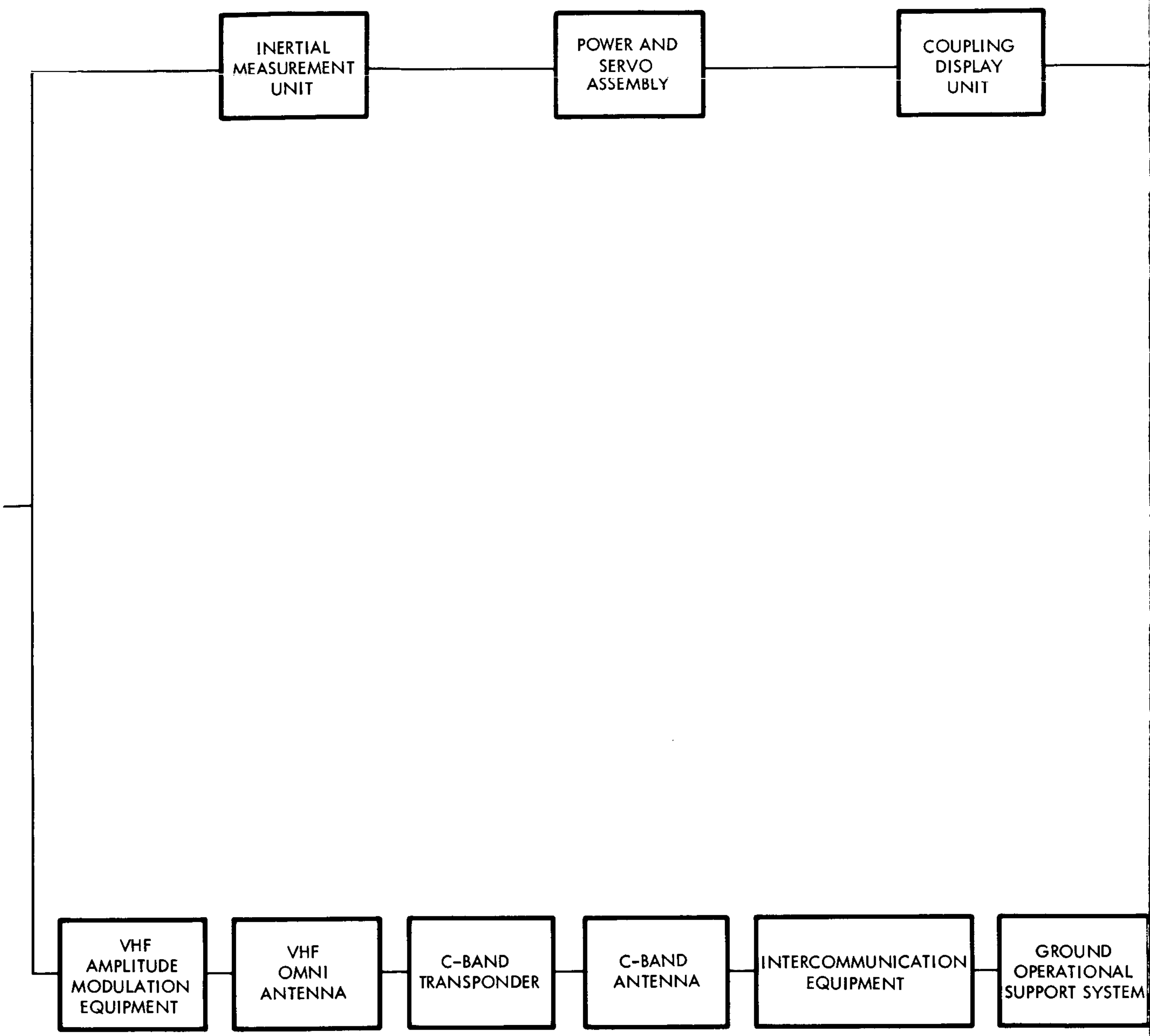
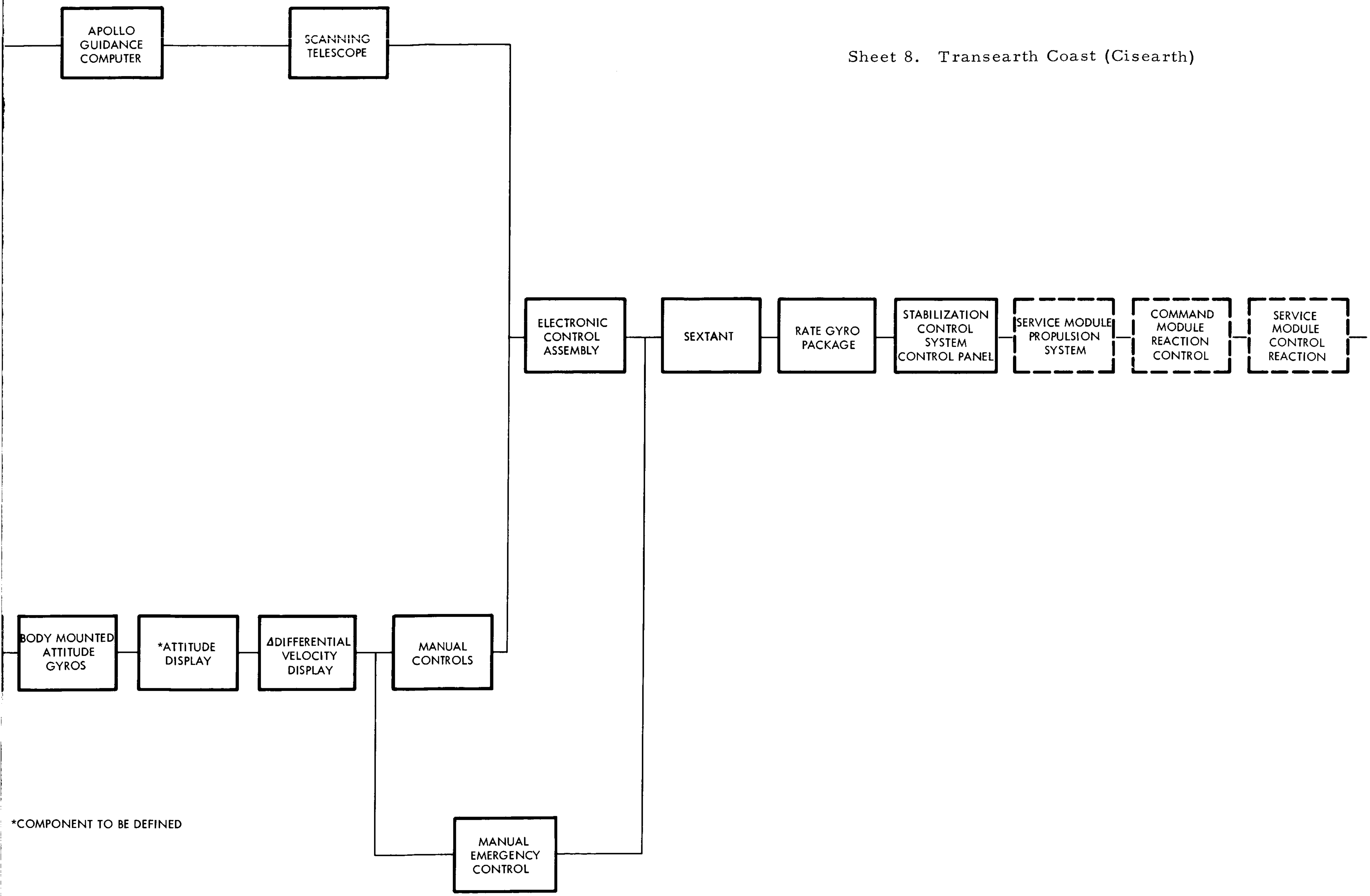


Figure 2. Crew Safety and Mission Success Logic Network

[redacted]


INERTIAL MEASUREMENT UNIT
POWER AND SERVO ASSEMBLY
COUPLING DISPLAY UNIT
VHF AMPLITUDE MODULATION EQUIPMENT
VHF OMNI ANTENNA
C-BAND TRANSPONDER
C-BAND ANTENNA
INTERCOMMUNICATION EQUIPMENT
GROUND OPERATIONAL SUPPORT SYSTEM

Sheet 8. Transearth Coast (Cisearth)



*COMPONENT TO BE DEFINED

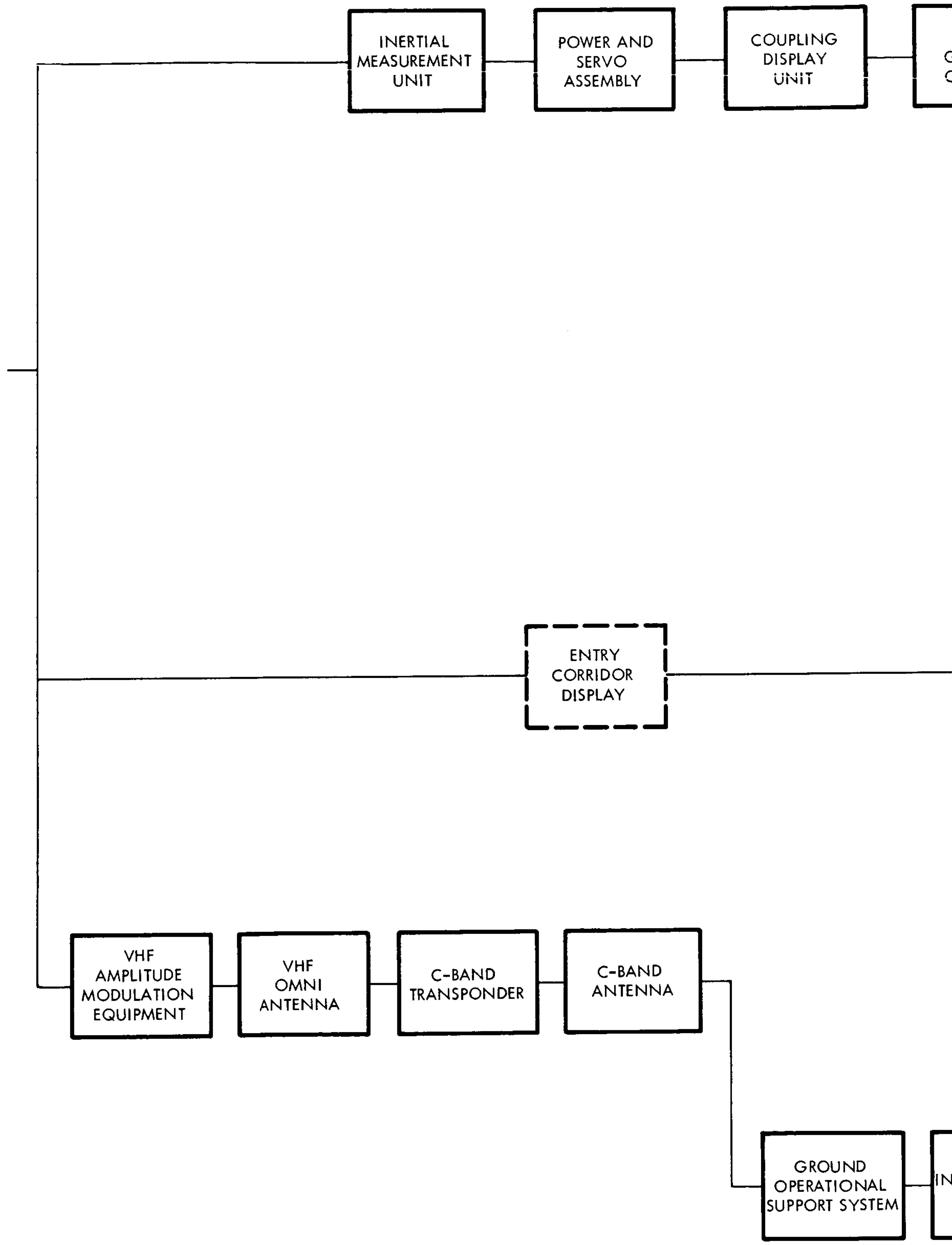
Figure 2. Crew Safety and Mission Success Logic Network

2

~~CONFIDENTIAL~~

[redacted]

(#1)


INERTIAL MEASUREMENT UNIT
POWER AND SERVO ASSEMBLY
COUPLING DISPLAY UNIT
ENTRY CORRIDOR DISPLAY
VHF AMPLITUDE MODULATION EQUIPMENT
VHF OMNI ANTENNA
C-BAND TRANSPONDER
C-BAND ANTENNA
GROUND OPERATIONAL SUPPORT SYSTEM

(#2)

Sheet 9. Entry

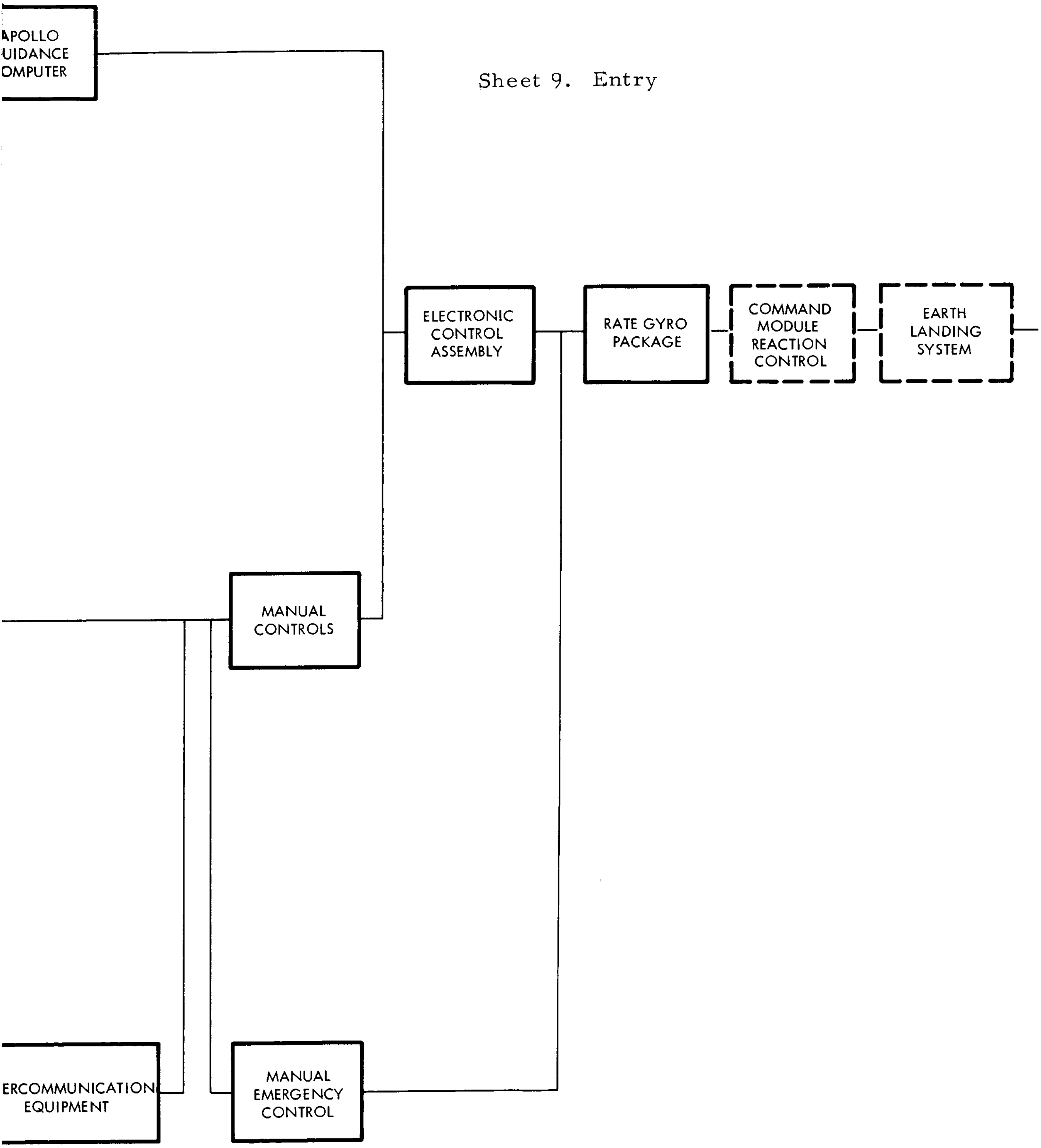
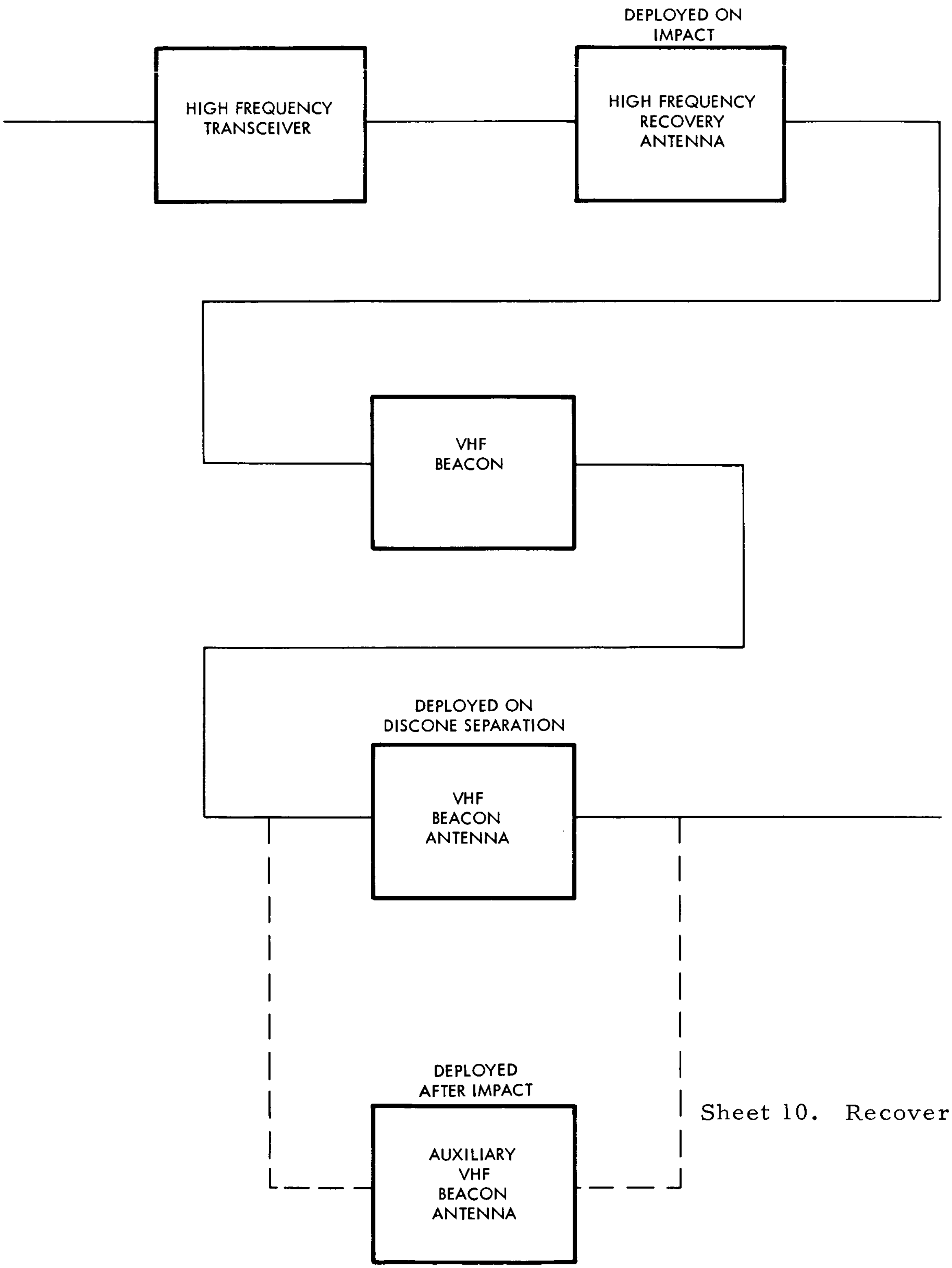


Figure 2. Crew Safety and Mission Success Logic Network

[redacted]



Sheet 10. Recovery

Figure 2. Crew Safety and Mission Success Logic Network

[redacted]

Table 3. Abort Criteria

System	Critical Equipment (Failure of any item creates mission abort.)
Navigation and guidance	Inertial measurement unit Power and servo assembly Coupling display unit Apollo guidance computer Sextant Scanning telescope Central timing unit
Stabilization and control	Body mounted attitude gyros Rate gyro package Flight director attitude indicator Gimbal position indicator Differential velocity indicator Manual controls Manual emergency controls Electronic control assembly Stabilization control system control panel
Communications and data	C-band transponder and C-band antenna Deep space information facility equipment and high-gain antenna Intercommunications equipment Very high frequency amplitude modulation equipment and VHF omni antenna
Reaction control	Reaction control system, command module Reaction control system, service module, failure of 2 quad modules
Propulsion	Service module propulsion system
Note: An equipment is considered as having failed only after failure of all redundancy (operational or standby) as well as all spares.	

COMMUNICATIONS AND DATA

DEEP SPACE INFORMATION FACILITY

Configuration Change Study

A reliability study was performed to determine the effect on the probabilities of mission success and crew safety caused by a contemplated configuration change in the communications and data subsystem. This modification proposes deletion of the C-band transponder, the VHF-AM transceiver, and the VHF-FM transmitter, using deep space information facility (DSIF) equipment to perform the functions of the deleted equipment. The effects on reliability can be obtained by modifying the reliability logic network to reflect the change. The results of this modification are given in Table 4.

Table 4. Communications and Data Subsystem Configuration Comparison

Configuration	Mission Failures Per Million Missions	Crew Safety Limits Exceeded Per Million Missions
Present	899	15
Proposed	308	14

The probability of exceeding emergency limits for crew safety includes the effects of the guidance function in each mission phase. Both the communications-and-data and the guidance-and-navigation functions must fail for crew safety to be jeopardized.

High-Gain Antennas Evaluation

A reliability evaluation was made for eight DSIF system configurations using high-gain antennas. These are shown in Figures 3 through 10 for all proposed modes of operation. The modes of operation (A through H) are listed in Table 5. The results of this study for each configuration and each mode are listed in Table 6.

[redacted]

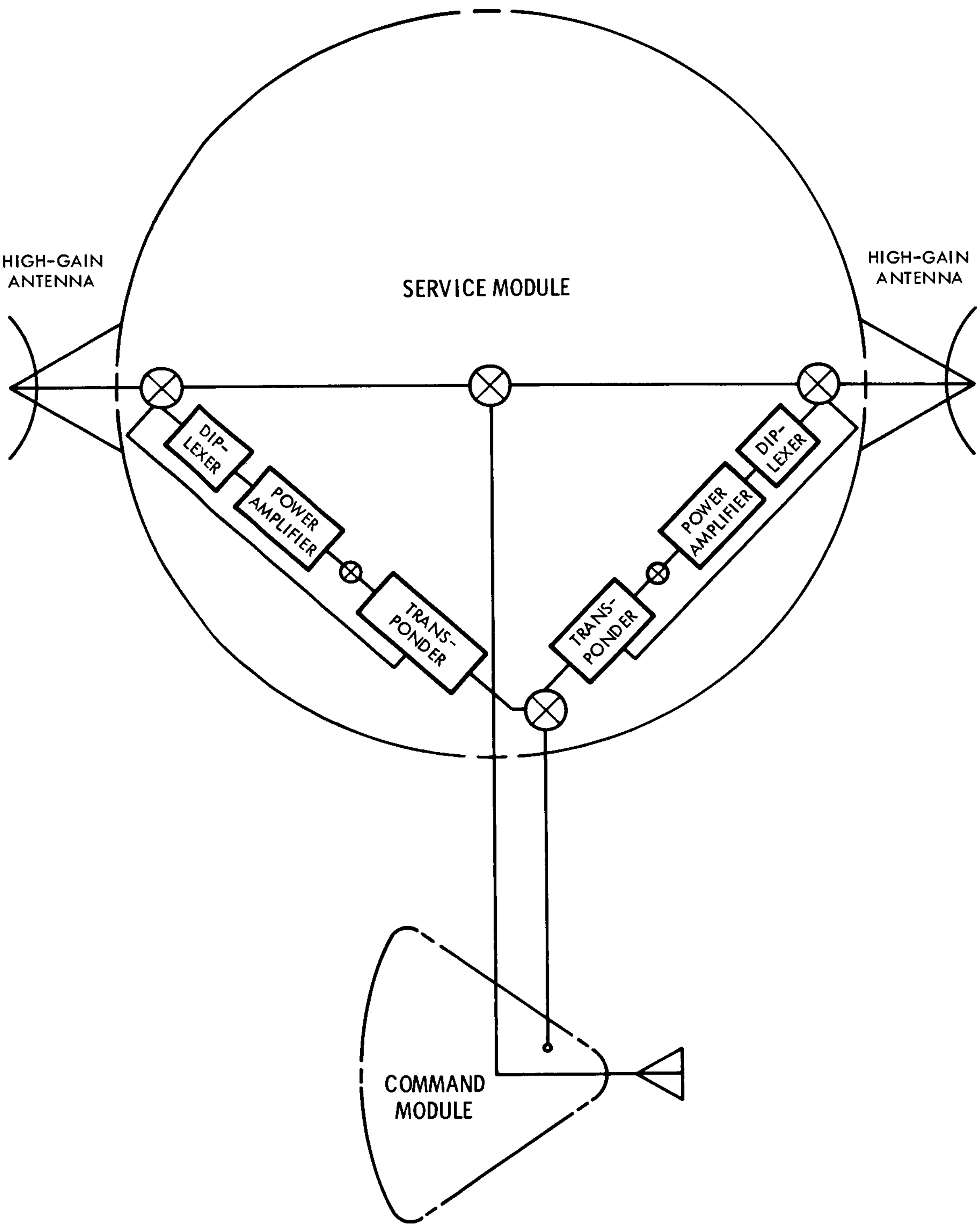


Figure 3. DSIF Equipment, Configuration A1

~~CONFIDENTIAL~~

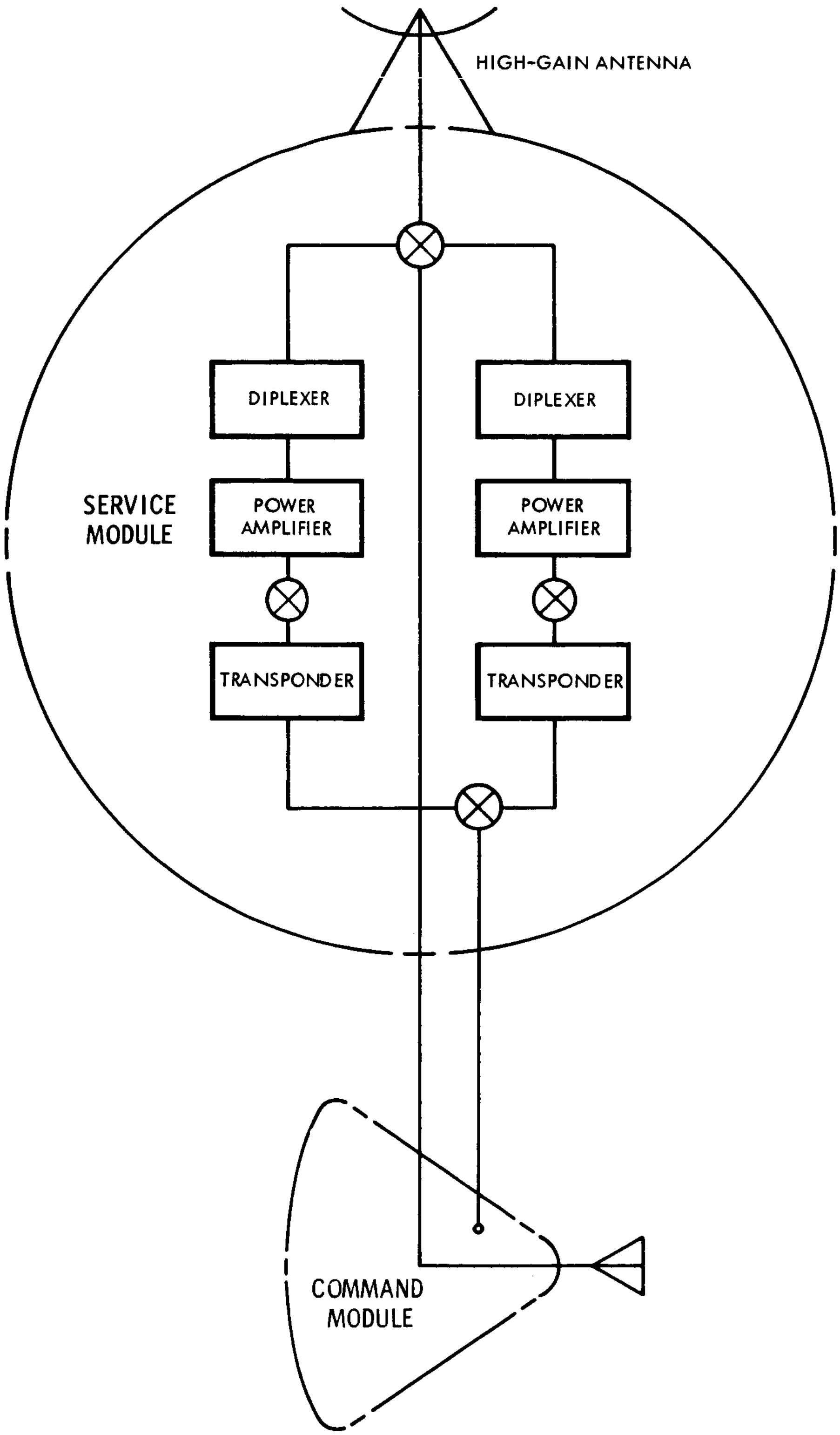


Figure 4. DSIF Equipment, Configuration A2

[redacted]

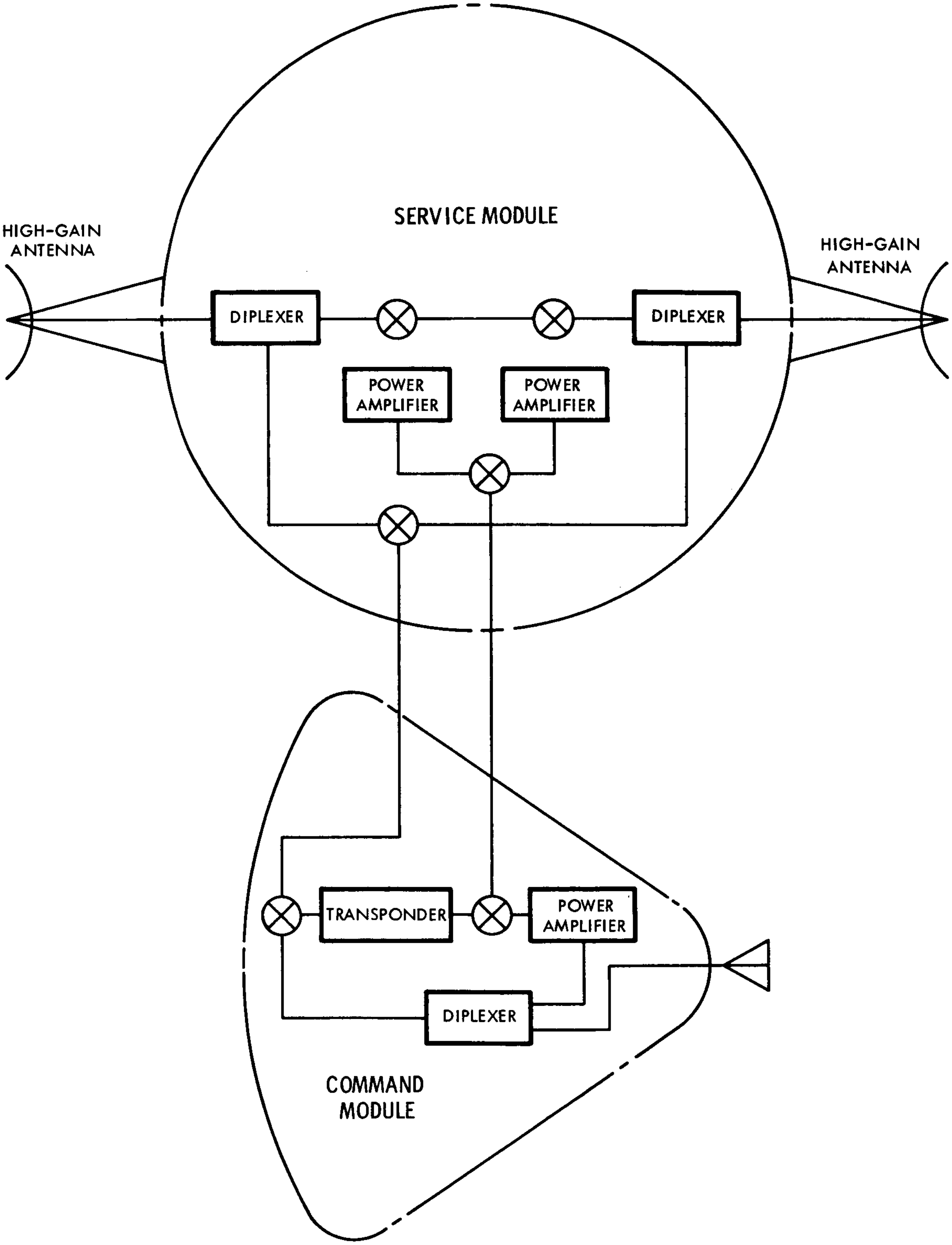


Figure 5. DSIF Equipment, Configuration B1

[redacted]

~~CONFIDENTIAL~~

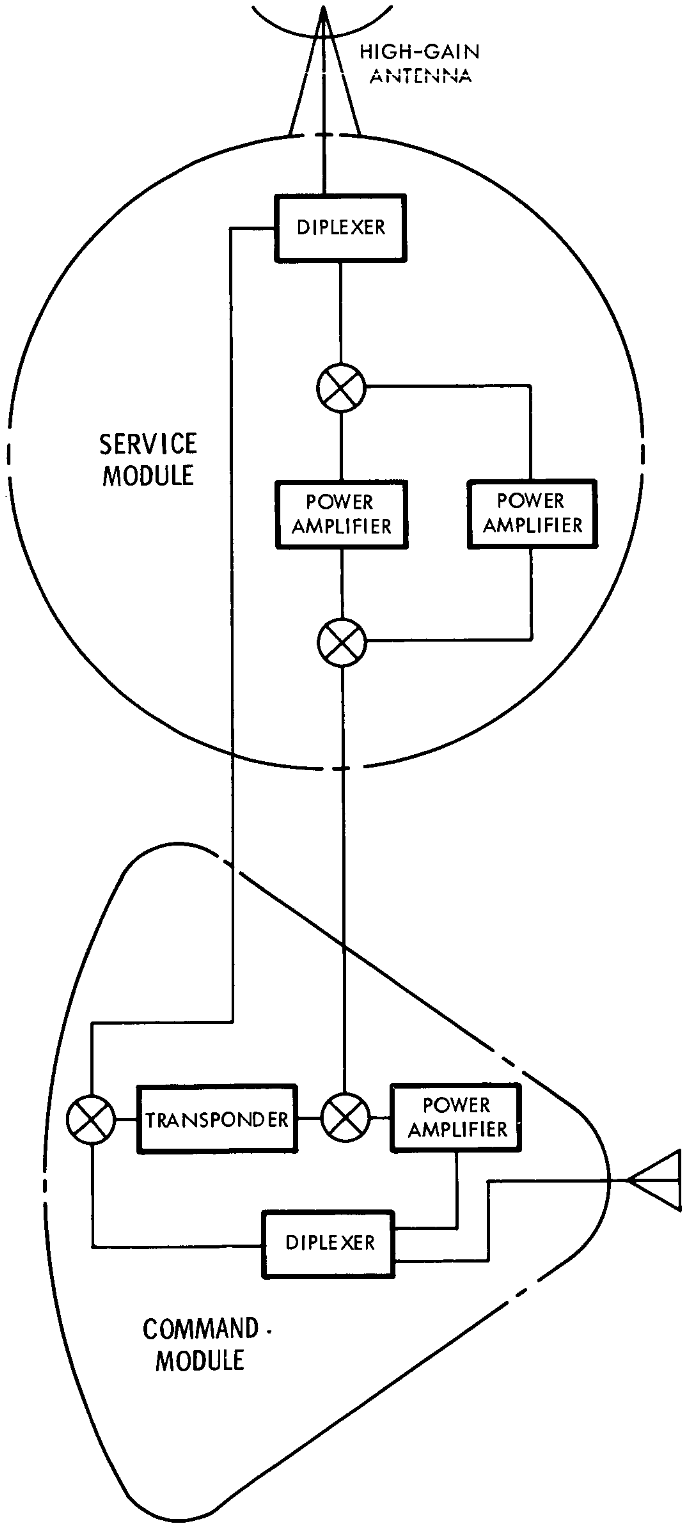


Figure 6. DSIF Equipment, Configuration B2

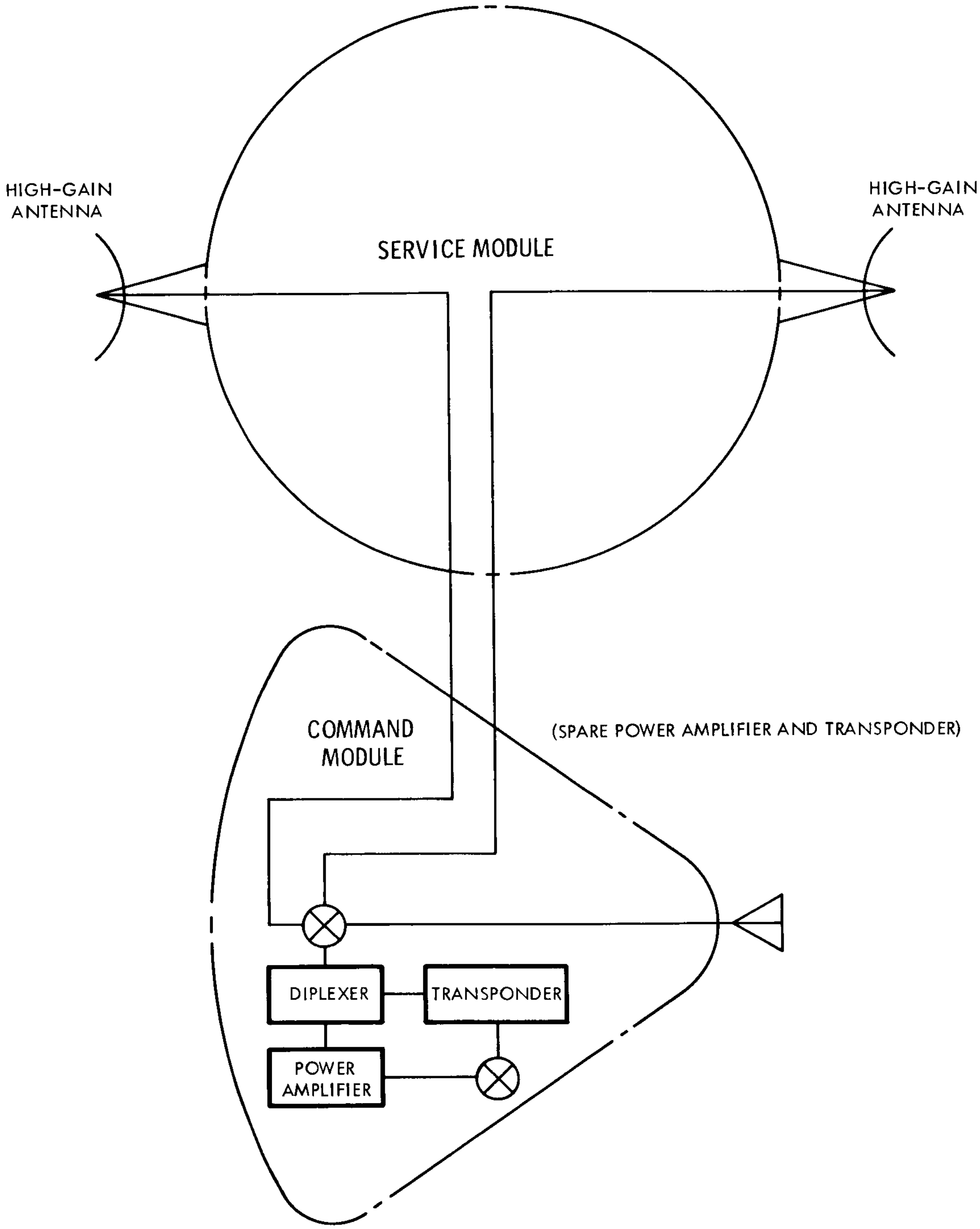


Figure 7. DSIF Equipment, Configuration C1

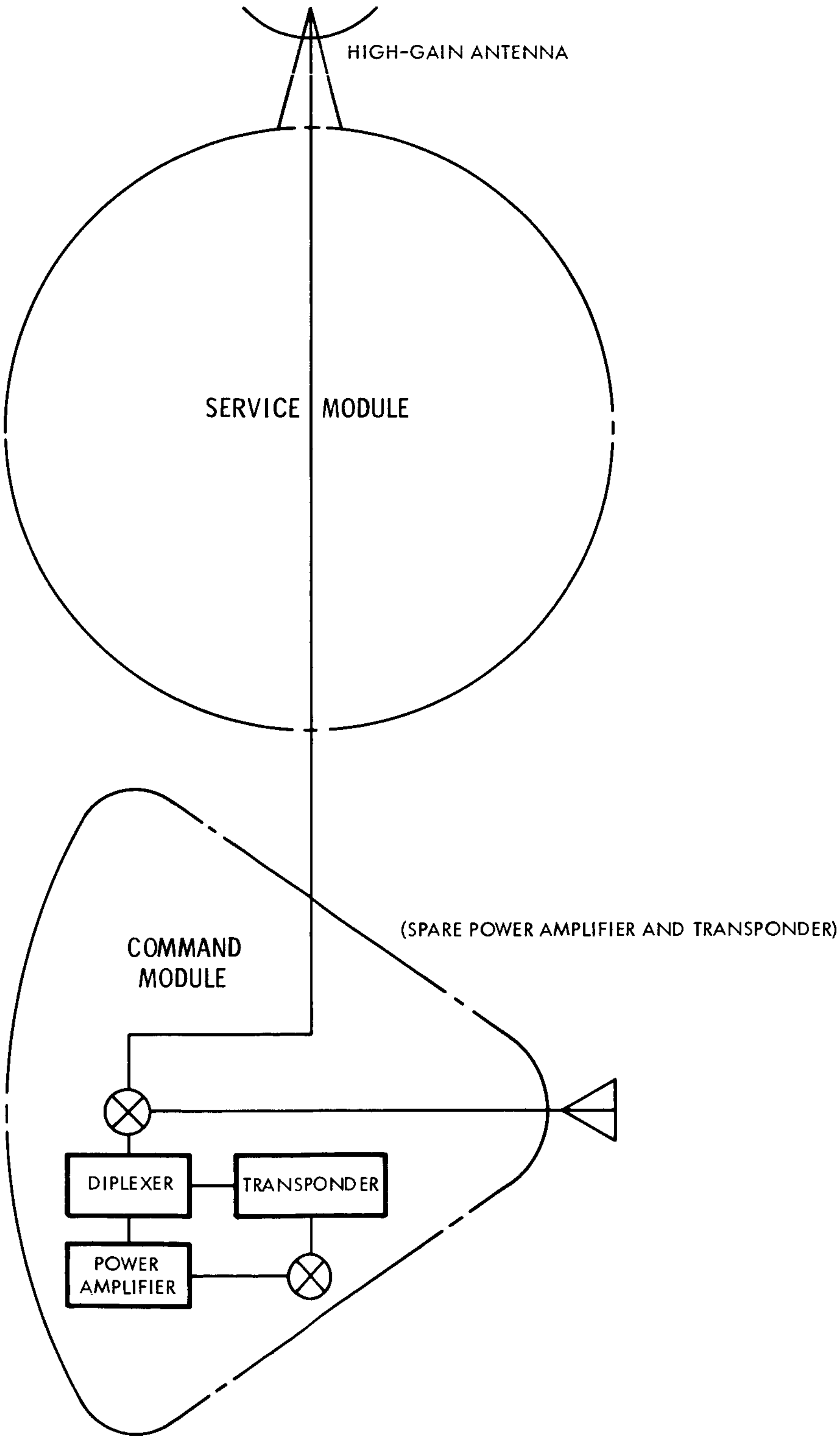


Figure 8. DSIF Equipment, Configuration C2

[redacted]

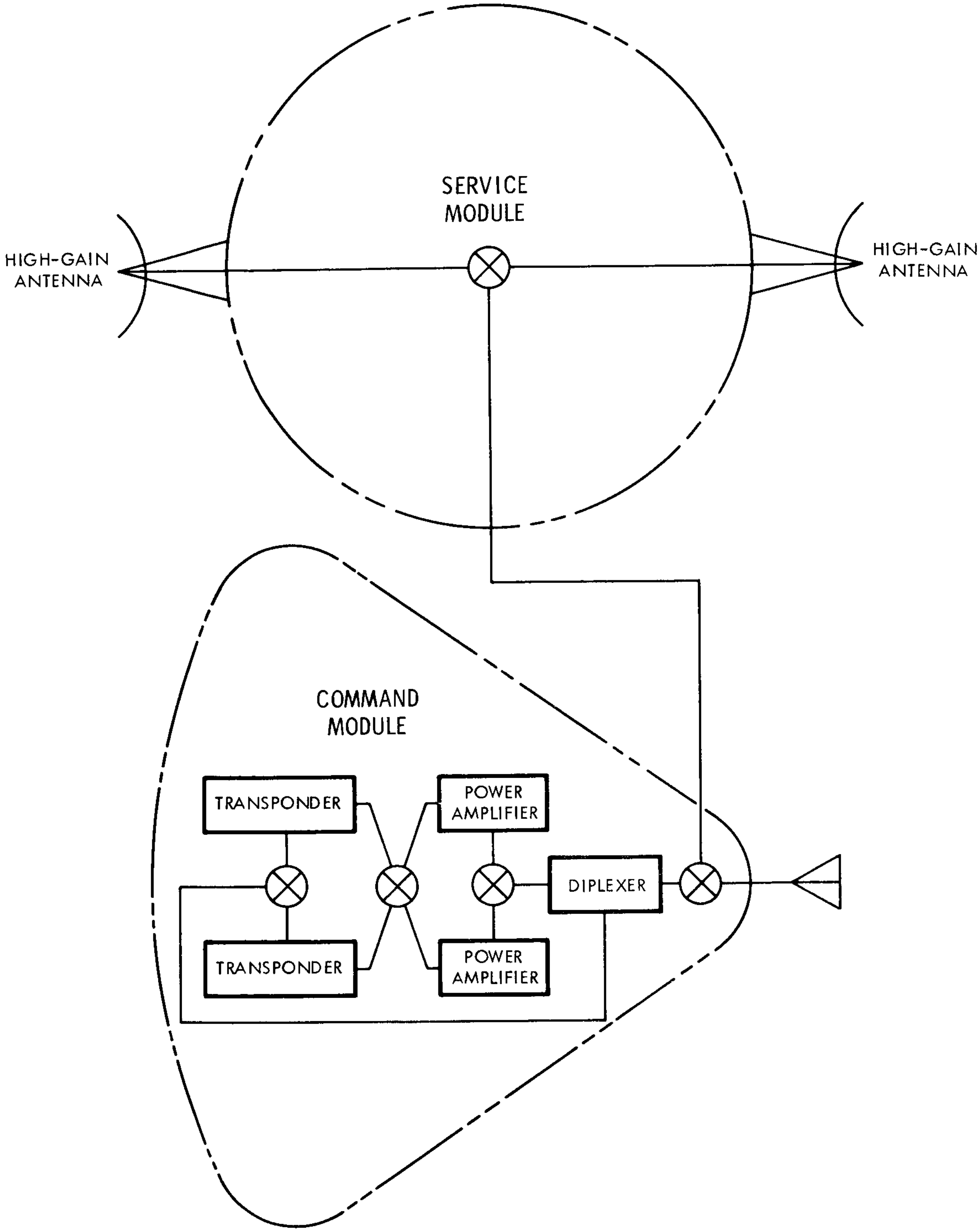


Figure 9. DSIF Equipment, Configuration D1

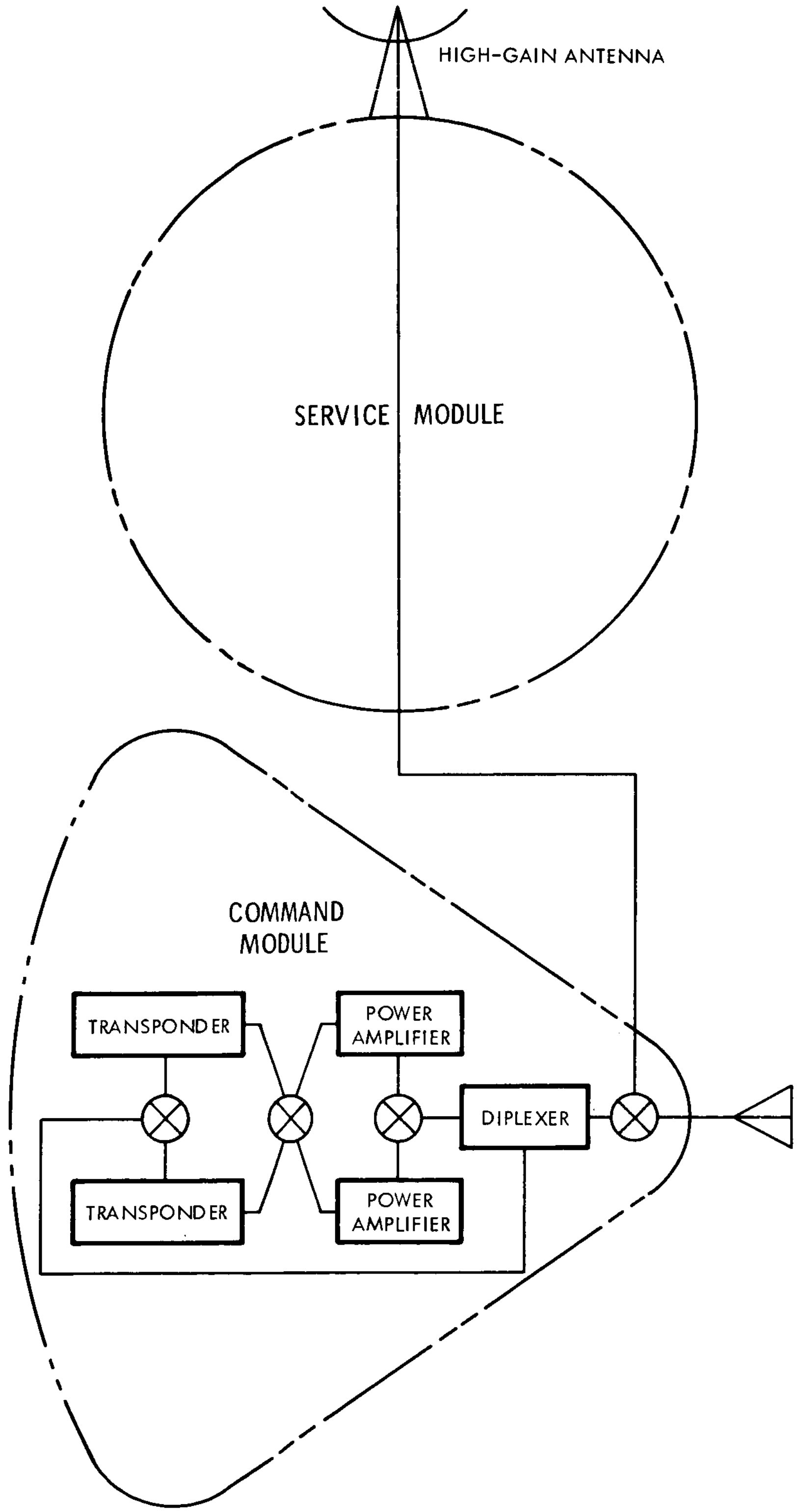


Figure 10. DSIF Equipment, Configuration D2

~~CONFIDENTIAL~~

Table 5. Deep Space Information Facility Modes of Operation

Operational Mode	Channel	Modulation Technique	Equipment Not Required	Transmitter Power (watts)
A	Telemetry	Pulse coded modulation and phase modulation		5
	Voice	Frequency modulation and phase modulation		
B	Ranging	Pseudo-random noise and phase modulation	High-gain antenna and power amplifier	0.2
C	Narrow-band telemetry	Pulse coded modulation and phase modulation	Power amplifier	0.2
D	Tape playback	Frequency modulation/ frequency modulation		5
	Voice	Frequency modulation		
E	Television	Frequency modulation		20
	Telemetry	Pulse coded modulation, phase modulation, and frequency modulation		
	Voice	Pulse amplitude modulation and frequency modulation		

[redacted]

[redacted]

Table 5. Deep Space Information Facility Modes of Operation (Cont)

Operational Mode	Channel	Modulation Technique	Equipment Not Required	Transmitter Power (watts)
F	Lunar excursion module to space-craft	Very high frequency pulse coded modulation and frequency modulation		10
	Voice	Amplitude modulation		
G	Voice	Frequency modulation	High-gain antenna or power ampli-fier	0.2
H	Key	Phase shift keying	High-gain antenna or power ampli-fier	0.2

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Table 6. Deep Space Information Facility Failures Per Million Missions

Transmitting Configuration		Operational Mode								
		Receive	A	B	C	D	E	F	G	H
A	Reliability using 2 high-gain antennas (Figure 3)	57	102	57	58	102	102	102	101	57
	Reliability using 1 high-gain antenna (Figure 4)	57	471	57	427	471	471	471	101	57
B	Reliability using 2 high-gain antennas (Figure 5)	7576	7583	7576	7576	7583	7583	7583	7576	7576
	Reliability using 1 high-gain antenna (Figure 6)	7576	7949	7576	7943	7949	7949	7949	7578	7576
C	Reliability using 2 high-gain antennas (Figure 7)	57	64	57	58	64	64	64	63	57
	Reliability using 1 high-gain antenna (Figure 8)	57	433	57	427	433	433	433	63	57
D	Reliability using 2 high-gain antennas (Figure 9)	57	64	57	58	64	64	64	63	57
	Reliability using 1 high-gain antenna (Figure 10)	57	433	57	427	433	433	433	63	57

~~CONFIDE~~[redacted]

[redacted]

These results indicate that all but two of the configurations would achieve the apportioned reliability, those being the configurations of Figures 5 and 6. These data also indicate that one high-gain antenna is sufficient to meet the reliability requirements. Apollo reliability engineering therefore recommended that either of the one-antenna configurations shown in Figures 8 and 10, be employed, depending upon the in-flight maintenance procedures and the associated allowable down-time for this system.

DSIF Spares

A reliability analysis was performed to determine the effect of a limited spares allocation for the DSIF equipment in the communications and data subsystem. Consideration was given to spares at the component and part level, as well as a completely spared DSIF. Table 7 outlines selected spares, their associated weight penalties, and the probabilities of subsystem failure.

Of the spares configurations considered, only an additional DSIF would achieve the required reliability. However, this configuration would not provide the most efficient use of spares. It seems probable that sparing of high-failure-rate components in the transponder and power amplifier components would achieve the necessary reliability with a minimum weight penalty.

This analysis showed that there is a need for further studies to determine realistically the most efficient use of spares in all of the electronic subsystems.

Table 7. Deep Space Information Facility Spares Analysis

Spares Configuration	Spares Weight (pounds)	Subsystem Failures Per Million Missions
None	None	9857
One power amplifier	16	3205
One transponder	16	6728
One complete DSIF	32	55
One transponder, one traveling wavetube, five relays	17	1140

PACKAGING CONCEPT

Increased packaging density and rearrangement of electronic equipment in the lower equipment bay has been proposed as a consequence of an effort to obtain a desired change in the command module center of gravity. A study was undertaken to determine the effect on reliability of the communications and data subsystem as a result of these changes. Results of this study are shown in Table 8. It is noted that all of the proposed changes result in degradation of reliability and therefore could not be recommended for incorporation in the packaging concept.

Table 8. Deep Space Information Facility Packaging Analysis

Change	Effect on Reliability	Cause
Higher packaging density	Degradation	Increased part temperature; Increased electromagnetic interference
Cordwood packaging technique	Degradation	Increased part temperature
Arrangement of equipment to optimize center of gravity	Degradation	Increased electromagnetic interference
Placement of HF transceiver and recovery beacon in the same package	Degradation	Malfunction in one unit may render the other inoperative

[redacted]

SERVICE MODULE PROPULSION

APPORTIONMENT AND PREDICTION

Component reliability allocations were revised consistent with the propulsion system reliability apportionment of 0.999770. Table 9 shows the results of reallocation for specified components, as well as the degree of development. The component requiring the greatest improvement is the rocket motor; the study shows that there is the need to decrease the state-of-the-art failure probability by a factor of 60. A detailed allocation of the rocket motor is in process and will be published in a later report.

LOGIC NETWORK AND MATHEMATICAL MODEL

Modification of the service module propulsion system resulted in the revised logic network shown in Figure 11. Major design considerations in this system were as follows:

Elimination of the positive expulsion devices in the fuel and oxidizer tanks in favor of propellant acquisition by positive acceleration, using the service module reaction control rocket motor

Addition of a heat exchanger (helium to fuel) in the helium pressurization line because of variations in tank pressure

Addition of burst discs and filters in the relief valves for leakage protection

Inclusion of the propellant flexible-feed lines as a separate item because of their length and complexity

The mathematical model for the service module propulsion logic network is as follows:

Mathematical Model - Service Module Propulsion System

$$R_{system} = R_1^2 \cdot \left[1 - (1 - R_2)(1 - R_3)\right] \cdot \left[1 - (1 - R_4 \cdot R_5^2)^2\right] \cdot$$

$$\left[1 - (1 - R_6^2)^2\right] \cdot \left[1 - (1 - R_8 \cdot R_9)(1 - R_7)\right].$$

[redacted]

[redacted]

$$\left[1 - (1 - R_{10})(1 - R_{11})\right] \cdot R_{12}^2 \cdot \left[1 - (1 - R_{13}) \cdot\right.$$

$$\left.(1 - R_{14})\right] \cdot R_{15} \cdot R_{16} \cdot R_{17} \cdot \left[1 - (1 - R_{18}^2)^2\right] \cdot$$

$$\left[1 - (1 - R_{19} \cdot R_{21})(1 - R_{20})\right] \cdot \left[1 - (1 - R_{22}) \cdot\right.$$

$$\left.(1 - R_{23})\right] \cdot R_{24}^2 \cdot R_{25} \cdot \left[1 - (1 - R_{26})(1 - R_{27})\right] \cdot$$

$$R_{28} \cdot R_{29} \cdot R_{30} \cdot \left[1 - (1 - R_{31}^2 \cdot R_{32}^2 \cdot R_{33}^2 \cdot R_{34}^2)^2\right] \cdot$$

$$\left[1 - (1 - R_{35}^2)\right] \cdot R_{36} \cdot R_{37} \cdot \left[1 - (1 - R_{38})^2\right]^2 \cdot R_{39}$$

FAILURE-MODE ANALYSIS

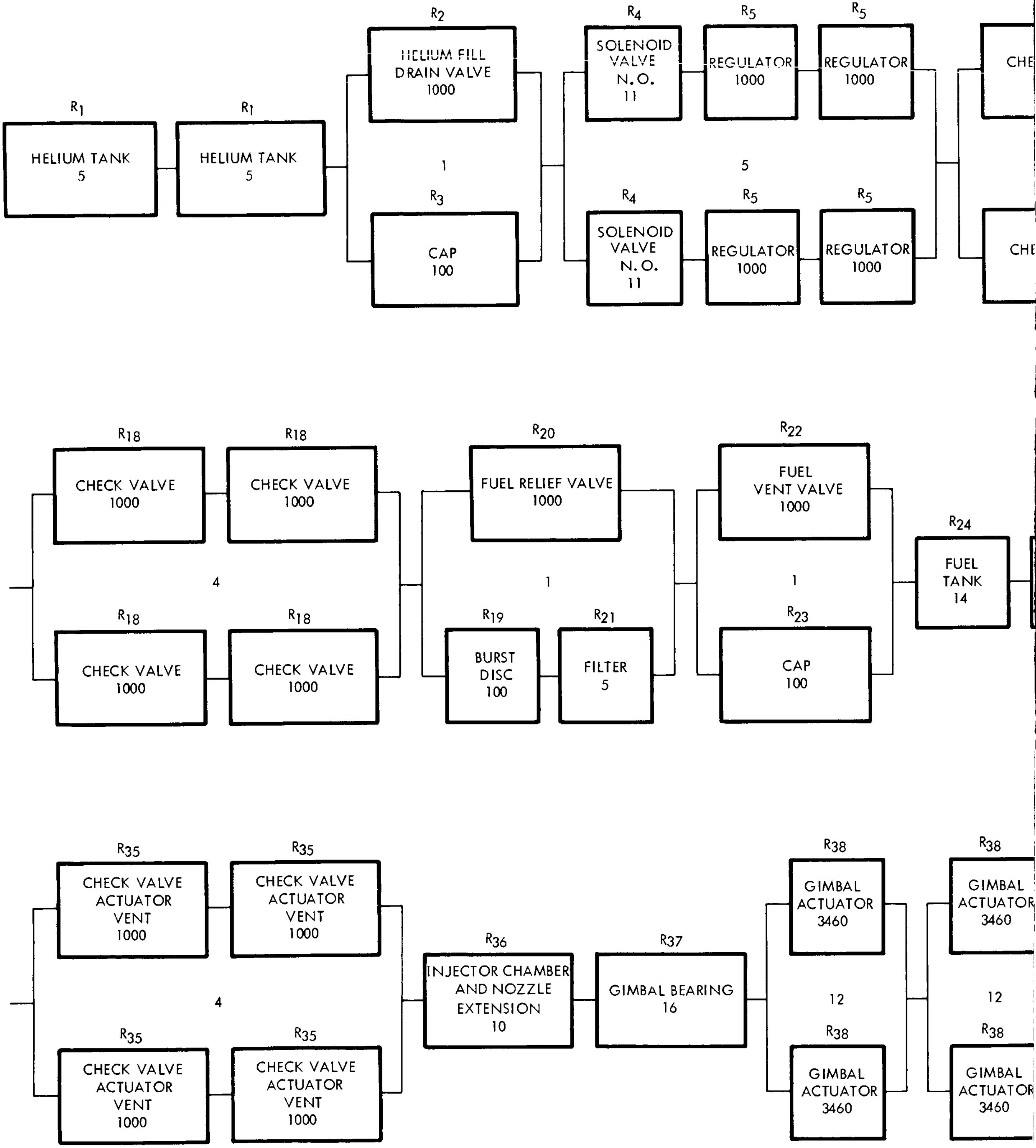
A failure-mode analysis of the service module propulsion system was generated from the system schematic diagram without the benefit of specific component details. The analysis, as shown in Table 10, is now available for component design and for consideration of critical-failure modes.

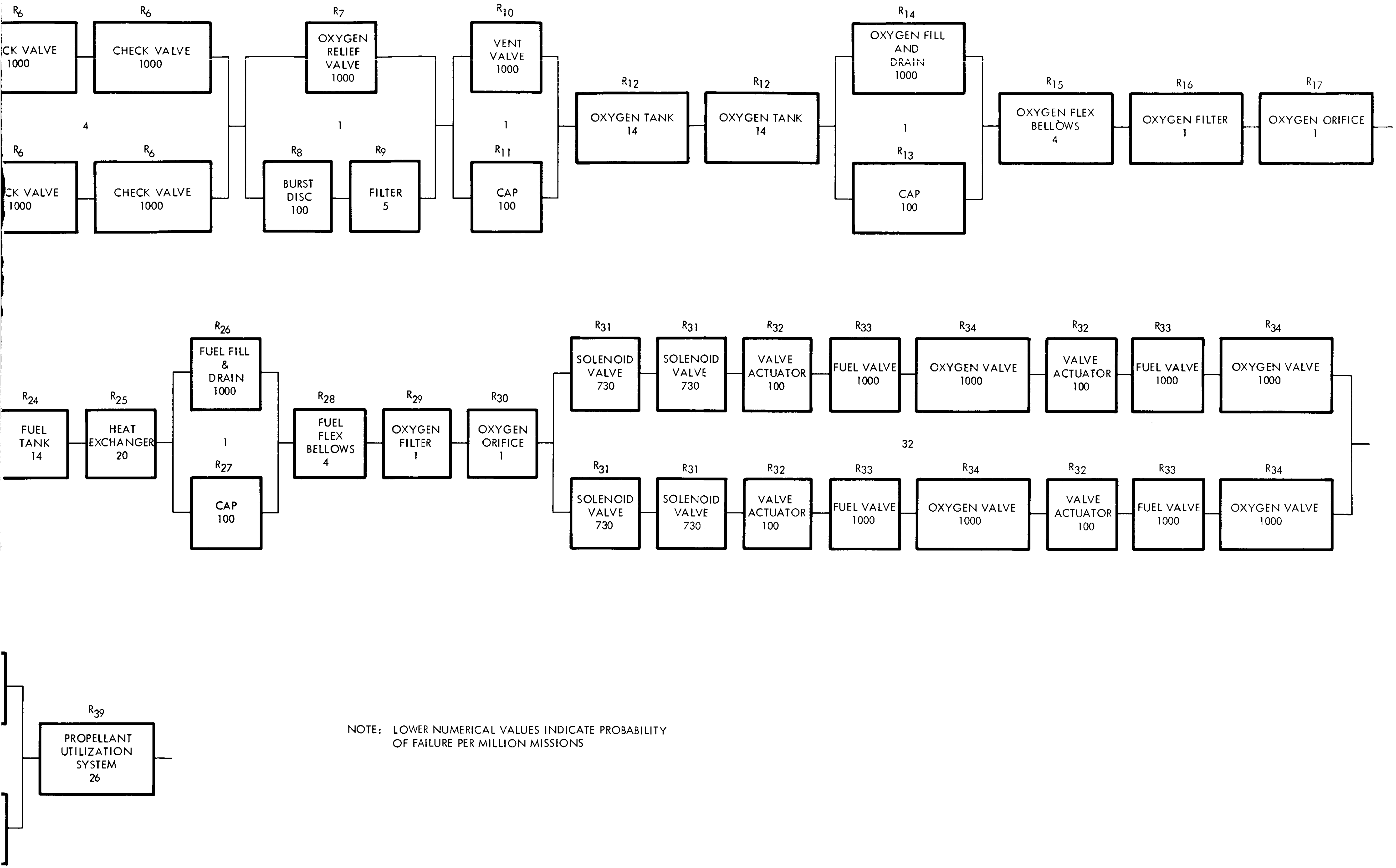
GIMBAL ACTUATOR COMPARISONS

Estimates of potential reliability were made for three types of gimbal actuators: electromechanical, hydraulic blow-down, and electrohydraulic. A detailed analysis is contained in SID 62-1220.

Engineering considerations dictated the selection of the electromechanical actuator, although the reliability is considered to be less than that of the other systems. Hydraulic systems achieve high reliability because of the large number of redundant components; however, the more difficult maintenance procedures inherent in hydraulic systems require additional considerations. A failure-mode analysis of the electromechanical actuator is shown in Table 11. The current design is being evaluated to find means of eliminating critical failure modes and improving reliability. Logic networks of the three types of gimbal actuators are shown in Figures 12, 13, and 14.

[redacted]


R1
HELIUM TANK
5
R1
HELIUM TANK
5
R2
HELIUM FILL DRAIN VALVE
1000
1
R3
CAP
100
R4
SOLENOID VALVE N.O.
11
R5
REGULATOR
1000
R5
REGULATOR
1000
5
R4
SOLENOID VALVE N.O.
11
R5
REGULATOR
1000
R5
REGULATOR
1000
R18
CHECK VALVE
1000
R18
CHECK VALVE
1000
4
R18
CHECK VALVE
1000
R18
CHECK VALVE
1000
R20
FUEL RELIEF VALVE
1000
1
R19
BURST DISC
100
R21
FILTER
5
R22
FUEL VENT VALVE
1000
1
R23
CAP
100
R24
FUEL TANK
14
R35
CHECK VALVE ACTUATOR VENT
1000
R35
CHECK VALVE ACTUATOR VENT
1000
4
R35
CHECK VALVE ACTUATOR VENT
1000
R35
CHECK VALVE ACTUATOR VENT
1000
R36
INJECTOR CHAMBER AND NOZZLE EXTENSION
10
R37
GIMBAL BEARING
16
R38
GIMBAL ACTUATOR
3460
12
R38
GIMBAL ACTUATOR
3460
R38
GIMBAL ACTUATOR
3460
12
R38
GIMBAL ACTUATOR
3460



NOTE: LOWER NUMERICAL VALUES INDICATE PROBABILITY OF FAILURE PER MILLION MISSIONS

Figure 11. Service Module Propulsion System Logic Network

2

[redacted]

~~CONFIDENTIAL~~

Table 9. Service Module Propulsion System Component Reliability Allocation

Component	Operating Time (hours)	Probability of Failure (10^{-6})		State-of-the-Art	Method of Improvement
		State-of-the-Art	Allocated	Allocated	
Helium tank	336	27	5	5.4	Design safety margin, testing
Fill and drain valve, and cap	336	1	1	1	
Solenoid valve	1 (cycle)	11	11	1	
Regulator	336	2520	1000	2.52	Failure mode analysis, testing and possible redesign
Check valve	336	773	1000	<1	
Relief valve	336	1317	1000	1.32	
Burst disk	336	100	100	1	
Filter	336	101	5	20.2	Design safety margin, testing
Oxidizer tank	336	54	14	3.8	Design safety margin
Fuel tank	336	54	14	3.8	Design safety margin
Propellant utilization system	336		26		
Vent valve	336	1318	1000	1.32	
Heat exchanger	336	60	20	3	Design safety margin and combined stress analysis
Rocket engine	336	5880	98	60	Design safety margin and failure techniques

[redacted]

Table 10. Service Module Propulsion System Failure-Mode Analysis

Component	Failure Type	Corrective Action	Effect on Mission	Mission Failure Classification
Helium tank	Leakage Tank wall Fitting Over-pressure	High design reliability Brazed or welded joint Safety factor 2:1 100 percent inspection	Mission abort - loss of pressurized gas	Critical
Helium fill valve	Leakage	Redundant seal (cap)	None	Minor
Solenoid shut-off	Open	Required to close only after double failure	None	Minor
Shut-off	Closed	Redundant path for regulator operation	None	Minor
Regulator	Open	Redundant with another regulator	None	Minor
	Closed	No crew requirements	None	Minor
	Burst	Safety factor 2:1 100 percent inspection	Mission abort - loss of pressurized gas	Critical
Helium heat exchanger	Leakage	Brazed or welded joints 100 percent inspection Safety factor 2:1	Mission abort; loss of pressurized gas	Critical

[redacted]

[redacted]

Table 10. Service Module Propulsion System Failure-Mode Analysis (Cont)

Component	Failure Type	Corrective Action	Effect on Mission	Mission Failure Classification
Filter	Blockage	Oversize flow area	Mission abort; loss of propulsion to engine	Major
Check valve	Leak	Series-redundant	None	Minor
	Closed	Parallel-redundant	None	Minor
Burst disc	Leak	Redundant with relief valve	None	Minor
	Closed	Needed only after prior failures	None	Minor
Relief valve	Open	Redundant with burst disc	None	Minor
	Closed	Redundant with dual regulators	None	Minor
Vent valve	Leakage	Redundant with cap	None	Minor
Propellant tank	Leakage	Redundant seals at all pressure joints	Mission abort; loss of propulsion or pressurized gas	Critical
	Over-pressure	After prior failure relief valve regulators	None	Minor
		100 percent inspection	None	Minor

[redacted]

~~CONFIDENTIAL~~

Table 10. Service Module Propulsion System Failure-Mode Analysis (Cont)

Component	Failure Type	Corrective Action	Effect on Mission	Mission Failure Classification
Propellant fill valve	Leakage	Redundant with cap	None	Minor
Propellant utilization valve	Incorrect o/f ratio	Redundant with manual override	None	Minor
	Leaves more residual propellants	Redundant gaging system	None	Minor
		Engine operable under worst condition	None	Minor
Test points	Leakage contamination	Redundant with cap	None	Minor
		Filter in each test point as part of spacecraft	None	Minor
Flight Instrumentation points	Leakage	Brazed or welded joints	Mission abort; loss of propellant or pressurized gas	Critical
Thrust chamber	Excessive erosion	Design includes safety margin and fabrication quality control	Reduction in total impulse	Major

~~CONFIDENTIAL~~

Table 10. Service Module Propulsion System Failure-Mode Analysis (Cont)

Component	Failure Type	Corrective Action	Effect on Mission	Mission Failure Classification
Injector	Orifice plugged	Large number of orifices resulting in negligible mixture ratio change	Mixture ratio change	Major
		Pattern designed to prevent single oxidizer jet from impinging on chamber wall.	Excessive streaking	
	Burnout	Design includes safety margin	Mission abort	Critical
Propellant valve cluster	Leakage	Designed series-redundant against leakage	Mission degradation due to loss of propellants	Major
	Fails to open	Parallel-redundant; both valves must fail to cause a critical failure	Mission abort, no engine start	Critical
	Fails to close	Series-redundant; both parallel systems must fail to cause a critical failure.	Mission abort due to loss of shutdown	Critical

Table 10. Service Module Propulsion System Failure-Mode Analysis (Cont)

Component	Failure Type	Corrective Action	Effect on Mission	Mission Failure Classification
Pilot valve	Fails to open	Parallel-redundant system must fail for critical failure	Mission abort; no thrust buildup	Critical
	Fails to close	Series-redundant valve vents system for normal operation	Mission abort; no thrust termination	Critical
Check valve	Leakage	Designed series-redundant for protection against leakage	Mission degradation; loss of pressurizing fluid, affect on timing	Major
	Fails to close	Designed series-redundant for protection against leakage	Mission degradation; loss of pressurizing fluid, affect on timing	Major
	Fails to open	Design parallel-redundant	Propellant valve fails to close	Critical
Position indicator	Fails to indicate valve position	Redundant design	None	Minor
Gimbal actuator	Stuck ball screw	Overdesign, close manufacturing and quality control	No attitude control	Critical
	Motor failure	Redundant design	No attitude control	Critical
	Clutch failure	Redundant design	No attitude control	Critical
	Gear failure	Redundant design	No attitude control	Critical

Table 11. Electro-Mechanical Gimbal Actuator Failure-Mode Analysis

Component	Mode of Failure	Cause of Failure	Effects of Failure	Means of Detecting Failure	Corrective Action
Ball jack screw shaft	Fatigue	Overload	No actuation	None	Probability of this occurring is extremely low
	Flute	Galling and ball failures	Slow or no actuation	None	Adequate safety margin
Ball jack screw gear	Tooth failure	Contamination or binding	No operation	Autopilot sensing thrust vector	
Ball pickup finger	Galls and holds balls	Lack of lubrication	No effect	None	Remaining balls carry load without circulation
Ball jack screw ball	Fatigue	Overload	No effect; broken balls and forced into sump area	None	Remaining balls carry load and there is partial redundancy since all the balls are not working all the time
	Galling	Lack of lubrication	Galling of flute		
Ball jack screw gear train	Mesh	Misalignment and binding	No operation of thrust vector control in plane of failure	High motor current	
	Jammed	Galling or contamination	Degradation of actuator response	High motor current	
	Fatigue	Structural failure	One side of actuator inoperative	Autopilot sensing thrust vector error	Redundant in standby loop switching

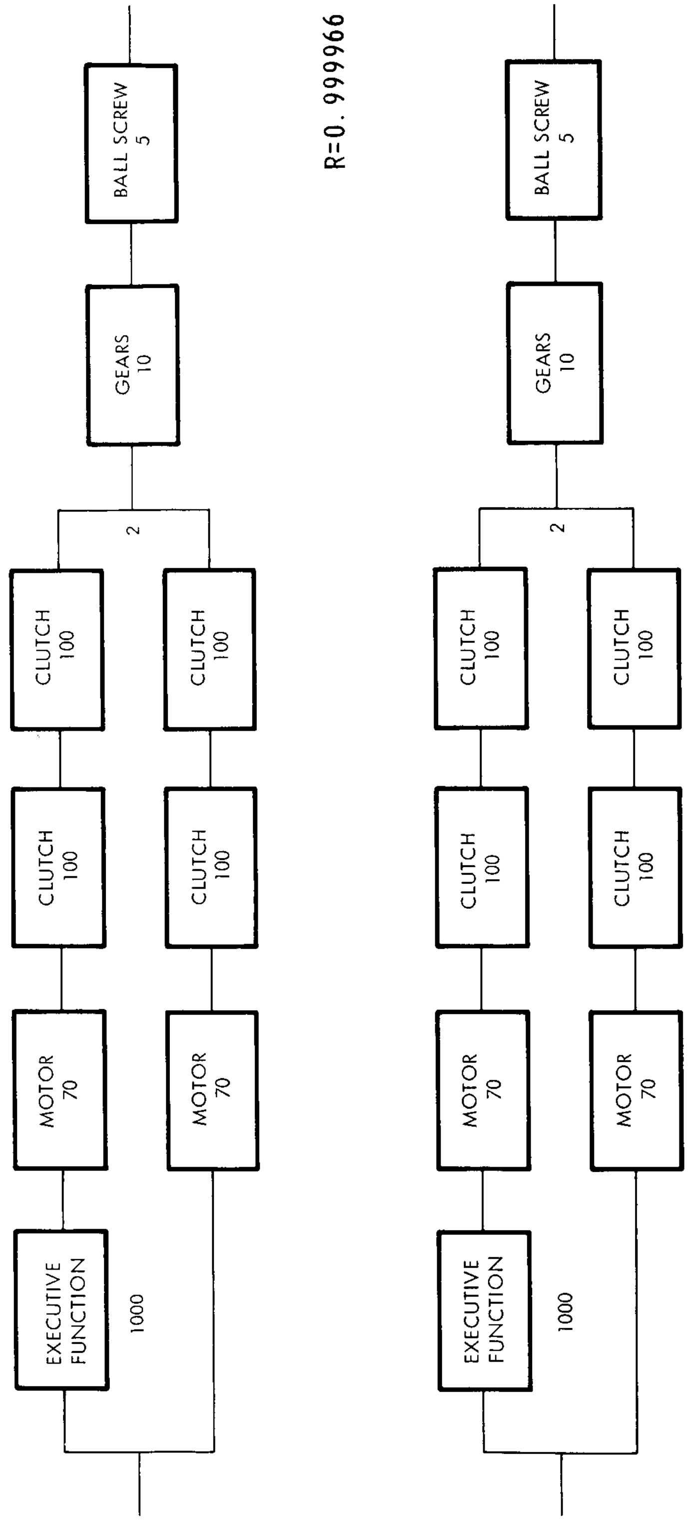
Table 11. Electro-Mechanical Gimbal Actuator Failure-Mode Analysis (Cont)

Component	Mode of Failure	Cause of Failure	Effects of Failure	Means of Detecting Failure	Corrective Action
Brushes, DC motor	Open	Broken lead	No operation of thrust vector control in plane of failure	No motor current	Redundant in standby loop
	Shorted	Faulty insulation	No operation of thrust vector control in plane of failure	High motor current	Redundant in standby loop
	Excessive wear	Operation in vacuum	No operation of thrust vector control in plane of failure	No motor current	Redundant in standby loop
Bearings, DC motor	Freeze	Faulty seals	No operation of thrust vector	High motor current	Redundant in standby loop
	Excessive drag	Contamination or binding	Slow operation	High motor current	Redundant in standby loop
Windings, DC motor	Open circuit	Broken lead	No operation of thrust vector control in plane	No motor current	Redundant in standby loop
	Short circuit	Faulty insulation	No operation of thrust vector control in plane	High motor current	Redundant in standby loop
Output shaft, DC motor	Jammed	Contamination of gears	No operation of thrust vector control in plane of failure	High motor current	Redundant in standby loop

Table 11. Electro-Mechanical Gimbal Actuator Failure-Mode Analysis (Cont)

Component	Mode of Failure	Cause of Failure	Effects of Failure	Means of Detecting Failure	Corrective Action
Output shaft, DC motor	Sheared (Decoupled)	Binding	No operation of thrust vector control in plane of failure	Autopilot sensing thrust vector error	Redundant in standby loop
Magnetic clutch coil	Open	Broken lead	Loss of thrust vector control in plane of failure	Autopilot sensing thrust vector error	Redundant in standby loop
	Shorted	Worn insulation	Loss of thrust vector control in plane of failure	Autopilot sensing thrust vector error	Redundant in standby loop
Magnetic clutch magnetic powder	Leakage	Seal failure	Loss of power and contamination of bearings	None	Redundant in standby loop
Magnetic clutch output shaft	Sheared (Decoupled)	Binding	No actuation of motor at no-load conditions	Motor current; autopilot sensing thrust vector error	Redundant in standby loop
	Frozen to body	Powder seizing, bearing freezing, or slip-ring failure	Direct coupling actuating engine to maximum deflection	Position indicator or excess motor current	Redundant in standby loop
Magnetic clutch body bearings	Freeze	Binding	Shear (decoupled); loss of thrust vector control	High motor current	Redundant in standby loop
	Excess drag	Misalignment or contamination	Slow operation	High motor current	Redundant in standby loop

~~CONFIDENTIAL~~



SYSTEM PROBABILITY OF FAILURE = 34 PER MILLION MISSIONS

NOTE:

NUMBERICAL VALUES ARE PROBABILITY OF FAILURES PER MILLION MISSIONS

Figure 12. Electro-Mechanical Gimbal Actuator Logic Network

~~CONFIDENTIAL~~

[redacted]

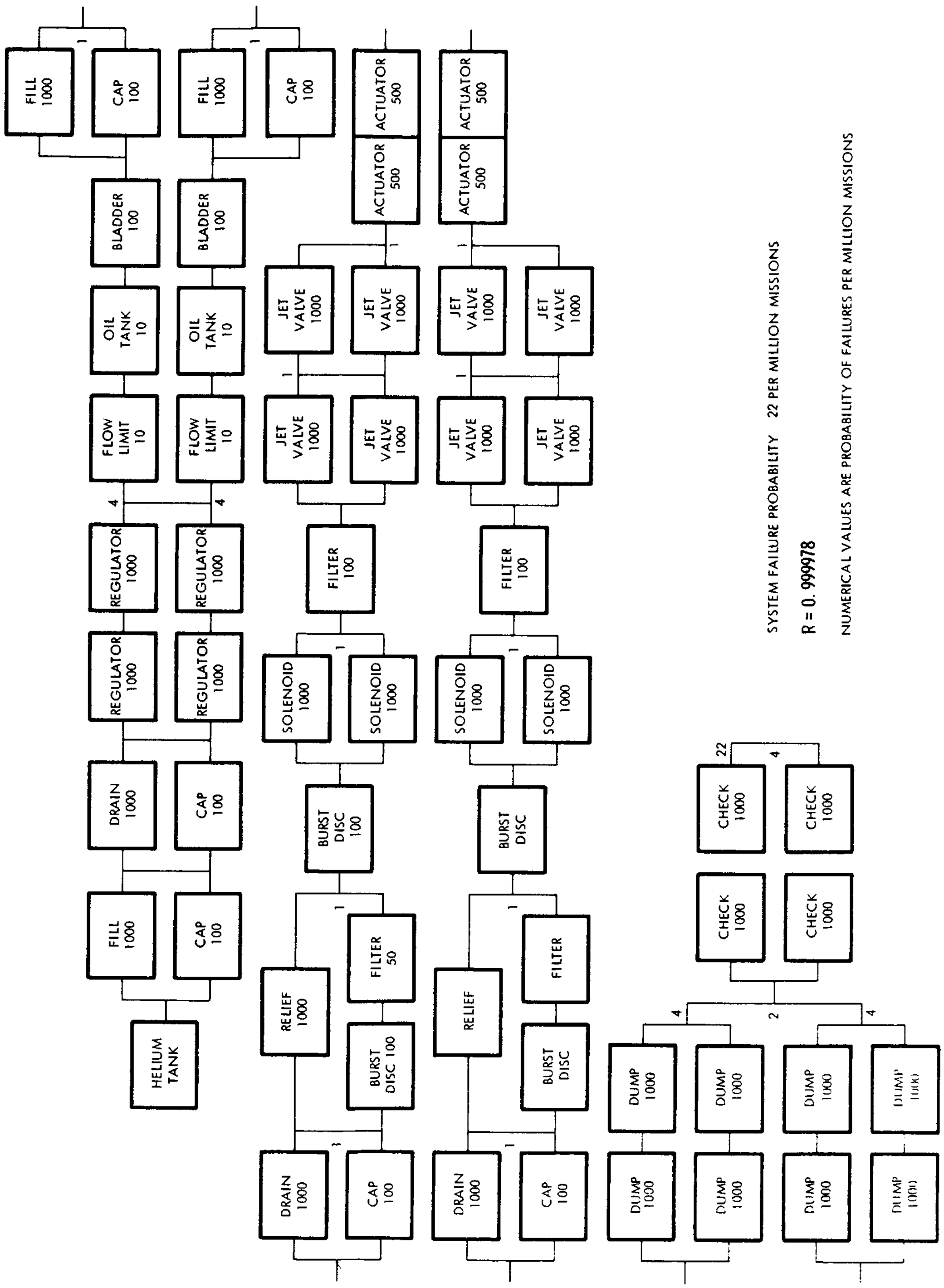
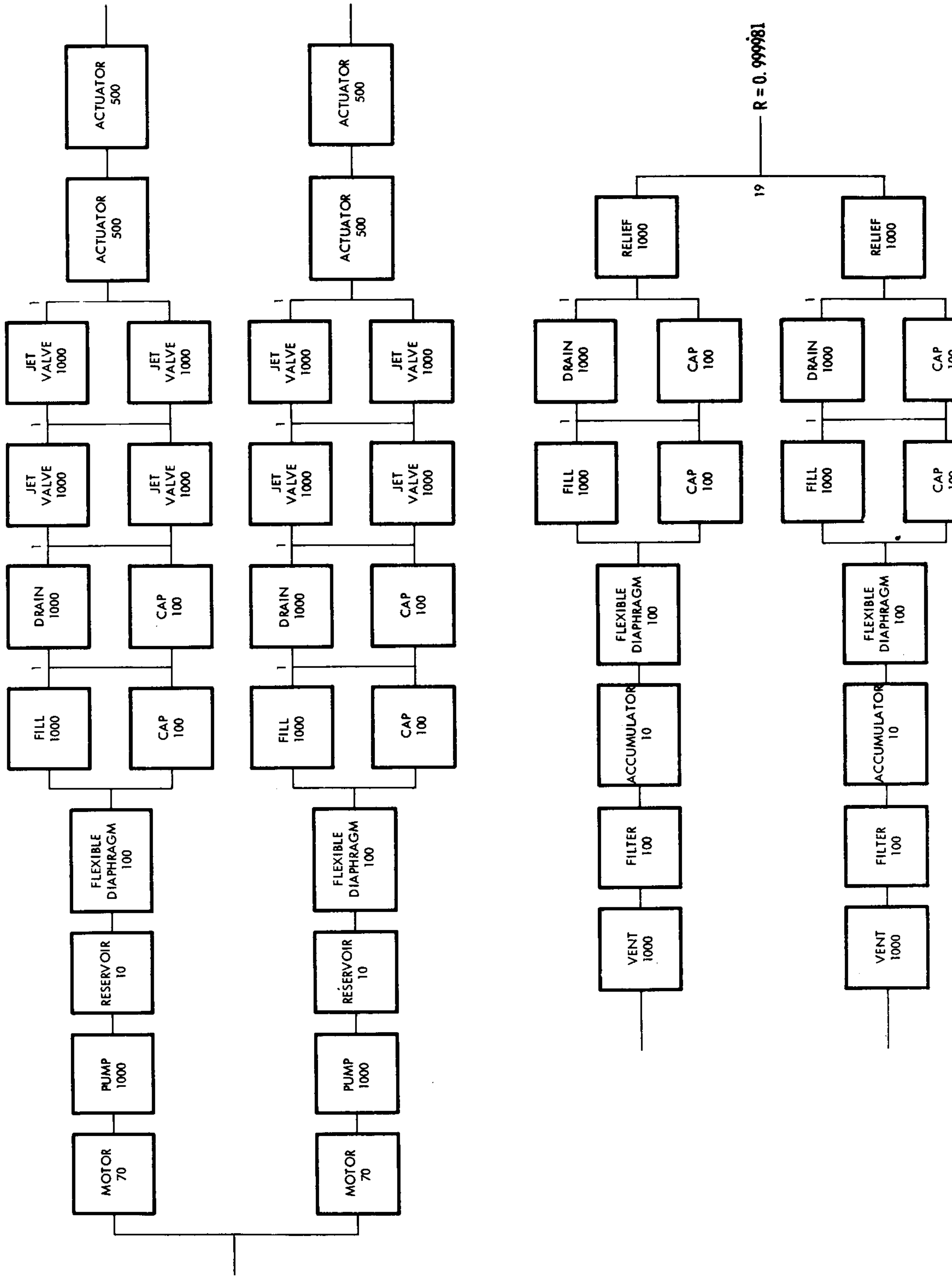


Figure 13. Hydraulic Blowdown Gimbal Actuator Logic Network

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~



SYSTEM PROBABILITY OF FAILURE = 19 MILLION MISSIONS
NUMERICAL VALUES ARE PROBABILITY OF FAILURES PER MILLION MISSIONS

Figure 14. Electro-Hydraulic Gimbal Actuator Logic Network

~~CONFIDEN~~[redacted]

[redacted]

SERVICE MODULE REACTION CONTROL

APPORTIONMENT AND PREDICTION

Reallocation of reliability for the reaction control quad system components is shown in Table 12. Component-failure probabilities are based upon the prescribed mission and the manner in which the component is used in the system. Basic failure rates were not derated for environmental conditions because laboratory test conditions were considered to be approximately the same as those to be encountered during flight.

LOGIC NETWORK AND MATHEMATICAL MODEL

As a result of a comparison study (SID 62-1193), a tentative selection of the quad system was made. A single-quadrant logic network is shown in Figure 15; combination of these quadrants would be made to provide for minimum-attitude-control capability using two out of the four quadrants.

The mathematical model for the service module reaction control system is as follows:

Helium Supply Subsystem

$$R_{H_e} = R_1 [R_2 + R_3 - R_2 \cdot R_3] [R_4 \cdot R_5 \cdot R_5 + R_4 \cdot R_5 \cdot R_5 - (R_4 \cdot R_5 \cdot R_5)^2]$$

Oxidizer or Fuel Subsystem

$$R_O = R_F = (2R_{10} - R_{10}^2)(R_{11} + R_{12} - R_{11} \cdot R_{12})(R_{13} + R_{14} \cdot R_{15} - R_{13} \cdot R_{14} \cdot R_{15})(R_{16})(2R_{17} - R_{17}^2)(R_{18} + R_{19} - R_{18} \cdot R_{19})(R_{20})$$

Engines

$$R_E = R_{30}^2 \cdot R_{31}^4$$

~~CONFIDENTIAL~~

Table 12. Service Module Reaction Control System Component Reliability Allocation

Component	Operating Time (hours)	Probability of Failure (10^{-6})		State-of-the-Art / Allocated	Method of Improvement
		State-of-the-Art	Allocated		
Helium tank	336	27	60	<1	
Burst disk	1 cycle	1	1	1	
Filter	336	101	101	1	
Solenoid valve	1 cycle	11	11	1	
Regulator	336	2520	1000	2.5	Improved design and extensive testing
Relief valve	336	1317	1317	1	
Vent valve	336	47	47	1	
Cap	336	3	4	<1	
Fill and drain valve	336	47	47	1	
Check valve	336	773	1000	<1	
Fuel tank	336	538	100	5.4	Trade-off with helium tank, R&D program on positive expulsion; 3 redundant bladders instead of 2
Oxidizer tank	336	538	100	5.4	
Flow meter	336	336	336	1	
Engine	336	4000	3000	1.3	

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

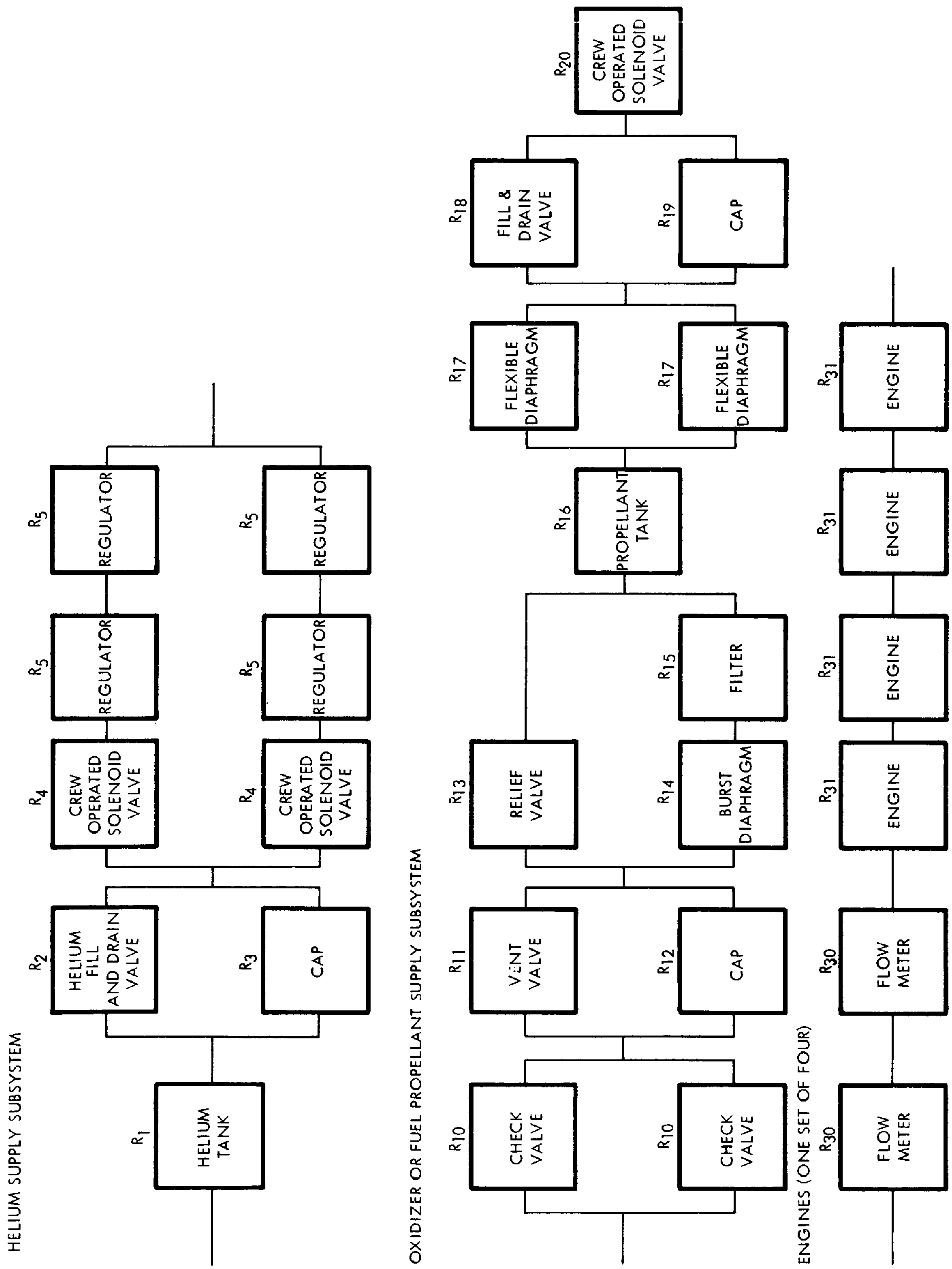


Figure 15. Service Module Reaction Control System Logic Network for One Quadrant

~~CONFIDENTIAL~~

Reaction Control System

$$R_{RCS} = R_{H_e} \cdot R_O \cdot R_F \cdot R_E$$

Numbers refer to respective components identified in Figure 15.

Mathematical models for the service module reaction control system, considering crew safety and mission success, are as follows:

Minimum Control (2 of 4 quadrants)

$$\text{Mission success} = \left[P_1^4\right]\left[P_2^4 + 4P_2^3\,q_2 + 6P_2^2\,q_2^2\right] + \left[4P_1^3\,q_1\right]\left[P_2^3 + 3P_2^2\,q_2\right]$$

$$\text{Crew safety} = \left[P_3^4 + 4P_3^3\,q_3 + 6P_3^2\,q_3^2\right]$$

Minimum Control (3 of 4 quadrants)

$$\text{Mission success} = \left[P_1^4\right]\left[P_2^4 + 4P_2^3\,q_2\right]$$

$$\text{Crew safety} = \left[P_3^4 + 4P_3^3\,q_3\right]$$

In which

P_1 = Probability of one module operating for 65 hours

P_2 = Probability of one module operating for 271 hours

P_3 = Probability of one module operating for 336 hours

$q_1 = (1 - P_1)\,P_{SOL}$

$q_2 = (1 - P_2)\,P_{SOL}$

$q_3 = (1 - P_3)\,P_{SOL}$

P_{SOL} = Probability of the shutoff valve working

These equations were derived from the binomial expansion of independent quadrants. Should three of the four quadrants be required for minimum attitude control, the quad system and one spare system would be capable of meeting the reliability allocation.

[redacted]

COMPARISON OF FIXED REACTION CONTROL TO DEPLOYABLE REACTION CONTROL

Heat transfer and control sources were considered in a reliability evaluation of deployable quadrants. Each quadrant would be stowed during boost and deployed from the service module surface after S-IVB thrust decay. Results of this study indicate the fixed-position quadrants to be more reliable than the deployable; however, the difference is not significant and other criteria should form the basis for selection.

Assumptions and definitions upon which the comparison of the fixed and deployable reaction control systems was based are as follows:

Time for fairing removal and deployment of reaction control system module is assumed to be 3.6 seconds (a conservative estimate).

Fixed structures are considered to be designed at least 0.999999 reliable.

Protective heat shielding is not considered in the reliability estimate of fixed-position reaction control system modules.

Fairing removal is accomplished by a combination of explosive bolts and springs.

Crew safety requires that two out of the four reaction control system modules must be successful.

Fairing removal and deployment redundances with engine firing are not considered in the analyses.

Tables 13, 14, and 15 and Figures 16 and 17 summarize the study results. The mathematical model used for fixed and deployable reaction control systems is as follows:

Part and Component Reliability

$$r_n = e^{-\lambda t}$$

Service Module Reaction Control System Fixed-Design Reliability

$$R = \left\{ r_5 \cdot \left[1 - (1 - r_6)^2 \right] \cdot \left[1 - (1 - r_4^2)^2 \right] \cdot r_7 \cdot r_8 \right\}^4$$

Service Module Reaction Control System Deployable-Design Reliability

$$R = \left\{ r_1^5 \cdot r_2^2 \cdot \left[1 - (1 - r_3)^2 \right] \cdot r_4^2 \cdot r_5 \cdot r_7 \cdot r_8 \right\}^4$$

Mission Success*

$$P = \overbrace{P_s^4 \, P_m^4}^{t_1} \overbrace{\left[P_m^4 + 4P_m^3 q_m + 6P_m^2 \, q_m^2 \right]}^{t_2} +$$

$$\overbrace{P_s^4 \left[4P_m^3 \, q_m \right]}^{t_1} \cdot \overbrace{\left[P_m^3 + 3P_m^2 \, q_m \right]}^{t_2}$$

Crew Safety*

$$P = P_s^4 \left[P_m^4 + 4P_m^3 \, q_m + 6P_m^2 \, q_m^2 \right] + 4P_s^3 \, q_s \left[P_m^3 + 3P_m^2 \, q_m \right] +$$

$$6P_s^2 \, q_s^2 \left[P_m^2 \right]$$

In which*

P_s = Probability of success of fairing removal and deployment

q_s = Probability of failure of fairing removal and deployment

P_m = Probability of reaction control system module success

q_m = Probability of reaction control system module failure

t_1 = Time, earth launch to trans-earth injection

t_2 = Time, trans-earth injection to command-module-service-module separation

Table 13. Reliability Comparison of Fixed to Deployable Reaction Control System

Reliability Consideration	Fixed	Deployable
Reaction control system	0.948380	0.948376
Mission success	0.999357	0.999353
Crew safety	0.999987	0.999987

Table 14. Failure-Mode Analysis for Fixed and Deployable Reaction Control Systems

Proposed Design	Failure Mode	Probability of Failure ($x 10^{-6}$)	Result of Failure	Corrective Action
Fixed	Fairing release	1	Loss of module use	Redundant release
	Fairing separation	1	Loss of module use	Redundant with engine firing*
	Structural failure	1	Loss of module use	Design safety margin
Deployable	Actuation	1	Loss of module use	Redundant ignition
	Complete deployment	3	Loss of module use	Redundant with engine firing*
	Lock in deployed position	<1	Loss of module use	Redundant lock mechanism
	Structural failure	1	Loss of module use	Design safety margin

*Not considered in analysis

Table 15. Component Data for Service Module Reaction Control System

Part or Component	Failure Rate (λ) (per million hours)	Time (t) (Hours)	Reliability (r)
Hinge Pin	105	0.001	0.999999
Bracket	37.5	0.001	0.999999
Actuator	1530.0	0.001	0.999998
Spring	33.75	0.001	0.999999
Structure		336	0.999999
Explosive bolt			0.999
Fairing			0.999999
RCS module		336	0.987098
Failure data from Avco			

[redacted]

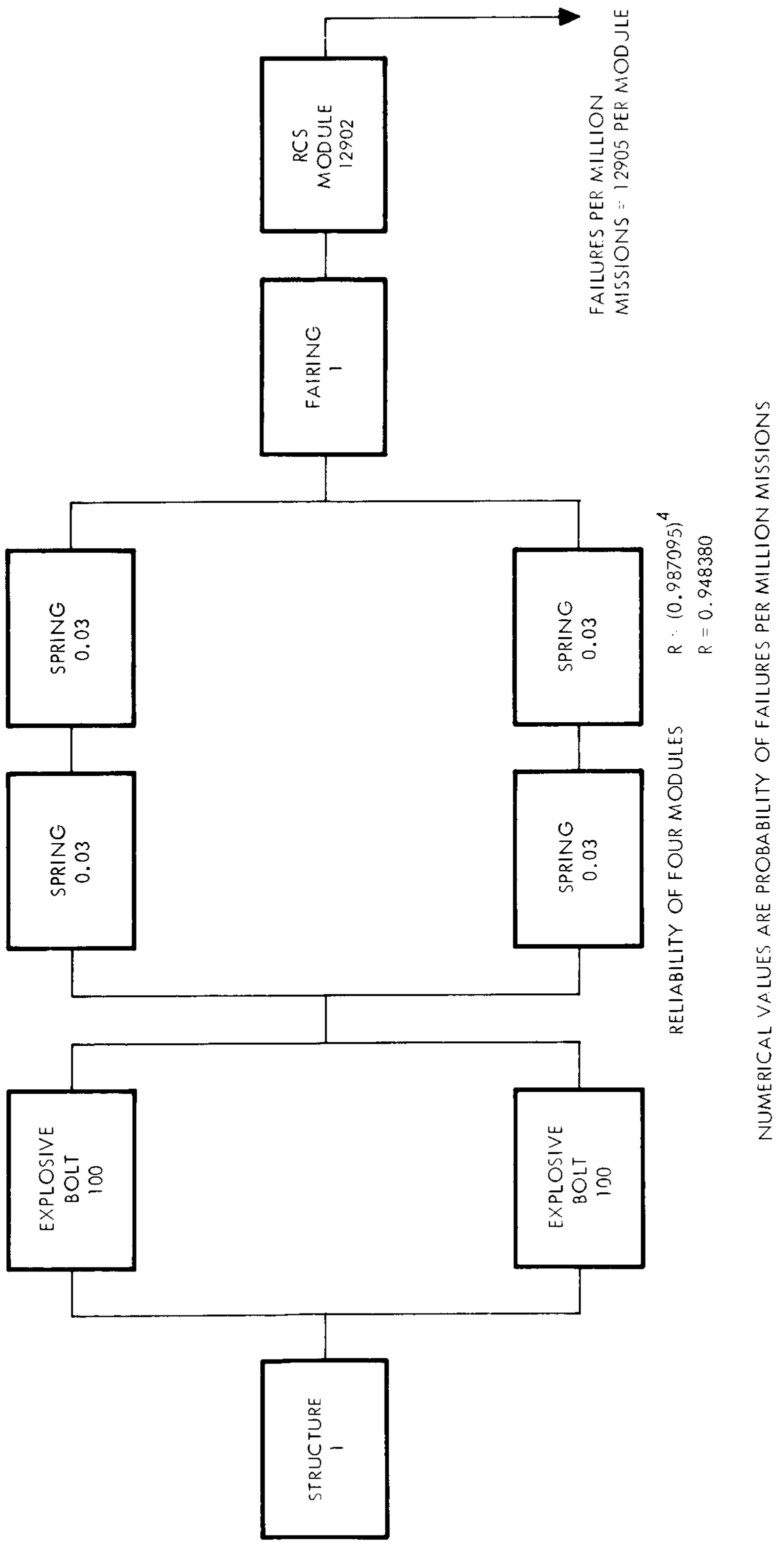
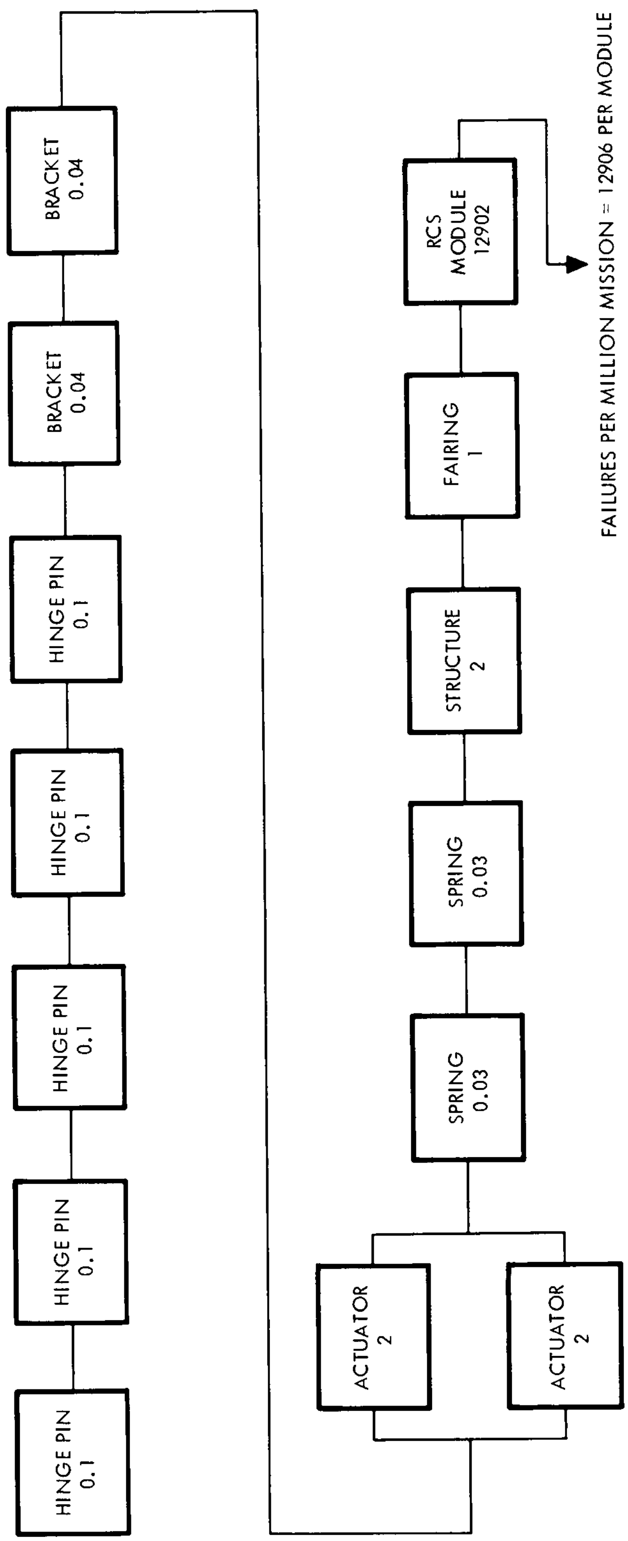


Figure 16. Fixed Reaction Control System Logic Network

[redacted]



RELIABILITY OF FOUR MODULES

$R = (0.987094)^4$

$R = 0.948376$

Figure 17. Deployable Reaction Control System Logic Network

EARTH LANDING

SINGLE-DROGUE PARACHUTE RECOVERY SUBSYSTEM

An evaluation was made of the feasibility of using a one-drogue system instead of the present two-drogue system in accomplishing the earth landing.

To meet the system reliability requirement, the single-drogue system would necessitate new ground rules. These would call for the successful operation of the single drogue and two out of the three main chutes, or, if the single drogue failed, all three main chutes. The existing system requires either the number 1 or the number 2 drogue and two of the three main chutes.

The validity of these ground rules depends on the capability of the main chutes to withstand the loads imposed on them if the drogue fails to work. The main chutes are designed to 64 q and tested to 96 q. Terminal q of the command module, aft heat shield forward, is 87. It would have to be assumed that, although the chutes might suffer damage, they would successfully land the command module.

Under the new ground rules, a problem exists that would have to be solved. The space capsule is stable apex forward. High q aborts are too much for the main chutes; therefore, the command module must have some means of obtaining an aft-heat-shield-forward attitude if the single drogue should fail. There was greater assurance of achieving the attitude by using the two-drogue system.

SHOCK ATTENUATION RELEASE SUBSYSTEM

The reliability of two methods proposed for releasing the shock attenuation strut assembly was evaluated. System A is a toggle release mechanism that consists of two cable cutters, each of which releases the tension in cables, thereby actuating all four toggle-release mechanisms.

System B is a sliding, collet-type latch release. An explosive charge, initiated by means of a dual-ignited, low-energy detonating cord (LEDC), causes shear pins to fail; this allows the energy of the explosive charge to drive the collet-retaining member to the unlocked position and allows release of the latch.

The reliability logic networks, and advantages and disadvantage of each system, are shown in Figure 18 and Figure 19, respectively.

~~CONFIDENTIAL~~

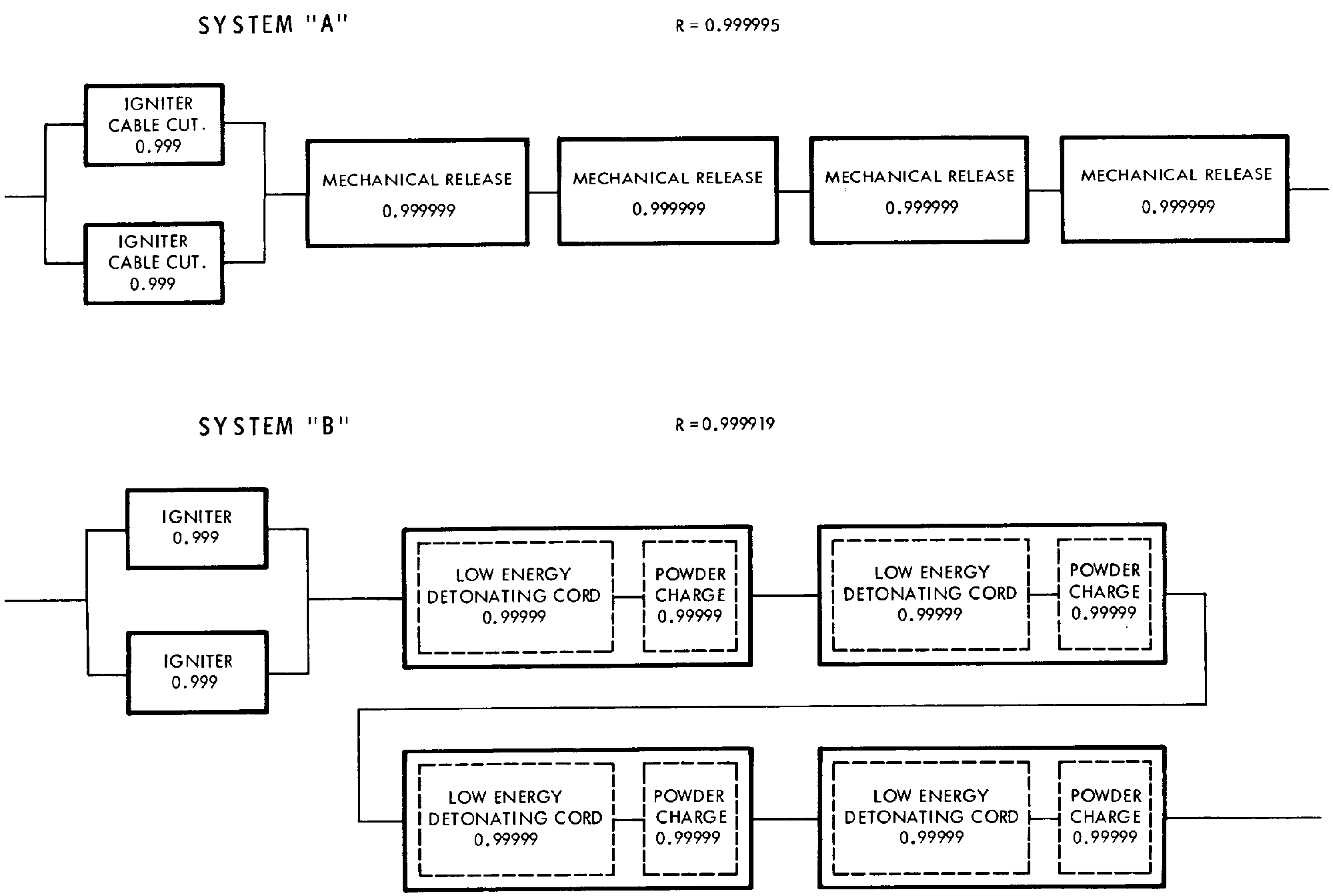
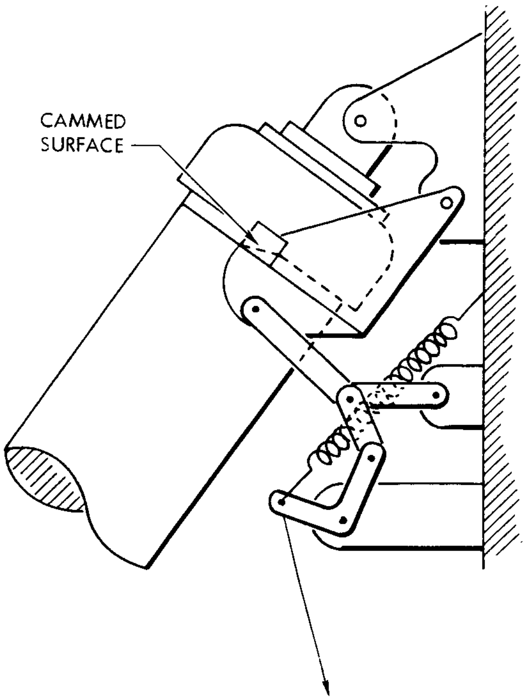


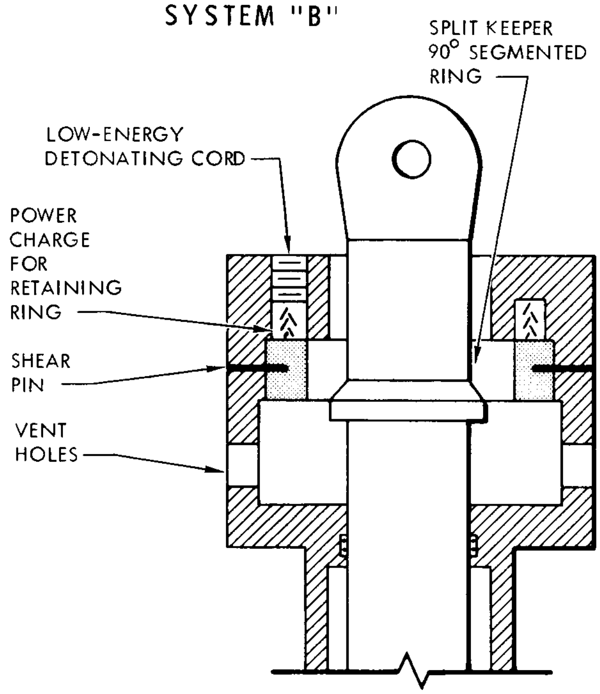
Figure 18. Shock Attenuation Release System Logic Networks for Systems A and B

~~CONFIDE~~[redacted]

SYSTEM "A"



SYSTEM "B"



ADVANTAGES

EITHER OF TWO CABLE CUTTERS WOULD RELEASE ALL SHOCK ABSORBERS.

MECHANICAL OPERATION CAN BE CYCLED FOR TEST.

SYSTEM MAY BE RIGGED WITH EASE.

SIMULTANEOUS RELEASE OF ALL SHOCK RELEASE MECHANISMS FROM ONE LOCATION.

NO CHANCE OF MECHANISM BEING JAMMED BY FLYING DEBRIS.

DISADVANTAGES

INADVERTENT FIRING RELEASES ALL SHOCKS.

ADVANTAGES

WEIGHT SAVING

DISADVANTAGES

THE MECHANISM MAY BE JAMMED BY LOOSE PIECES.

ALL 4 EXPLOSIVE CHARGES WOULD HAVE TO FIRE SUCCESSFULLY TO RELEASE THE SYSTEM.

RIGGING OF SYSTEM PRESENTS DIFFICULTIES.

SYSTEM CANNOT BE CYCLED FOR TEST.

Figure 19. Comparison of Configurations A and B Proposed for the Shock Attenuation Release System

[redacted]

BAROSWITCH RELIABILITY

A reliability evaluation was made of the use of one baroswitch versus two in series for three separate functions in each of the two channels of the earth landing sequencer. The probability of inadvertent closing (failure) of one and two baroswitches is shown below (assuming a probability of failure of 0.00001 for each baroswitch).

Probability of inadvertent closing

One baroswitch per channel per function = 10 per million

Total for system = 60 per million

Two baroswitches in series per channel per function = 0.0001 per million

Total for system = 0.0006 per million

Utilizing only one switch would save a small amount of weight, but it would permit no safeguard against an inadvertent firing which could be catastrophic to the crew. Having two in series decreases the reliability of operation minutely, as shown in Figure 20, but it increases crew safety by guarding against an inadvertent firing. An inadvertent firing could cause the release of the forward heat shield, deployment of the number 1 drogue, or deployment of the pilot chutes. Any of these events happening at the wrong time could prove fatal to the mission and the crew.

PARACHUTE DEPLOYMENT

A detailed reliability analysis was made of the deployment of the parachutes. This portion of the earth landing system has an estimated reliability of 0.99996. The logic network and assigned component reliabilities are shown in Figure 21.

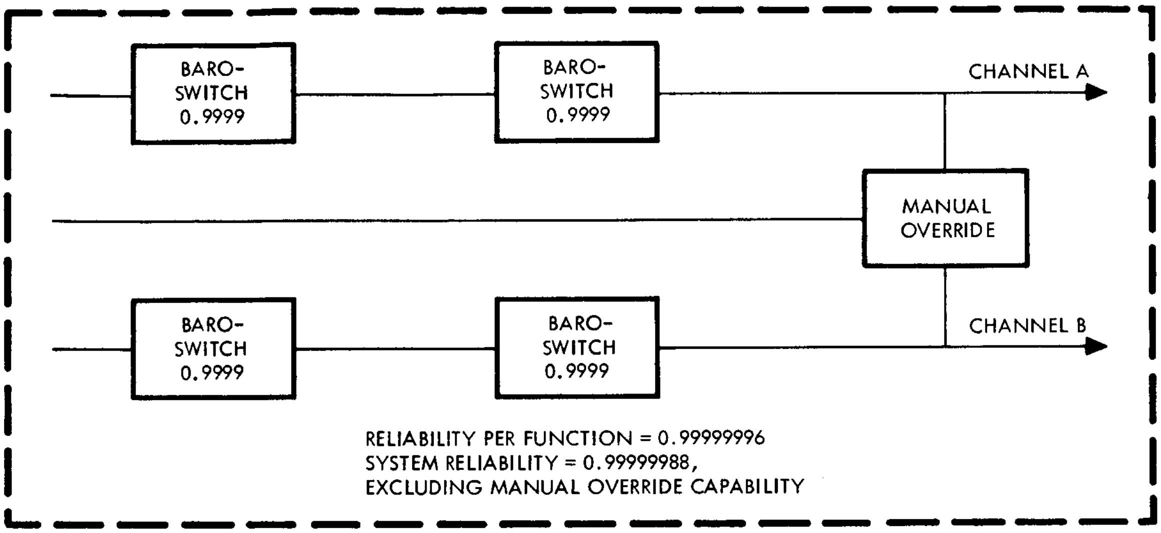
PERSONAL PARACHUTES

A reliability evaluation was made of the benefit derived from the use of personal parachutes by the crew.

The results of the evaluation are that the increase in crew survival reliability is quite small, but the benefits to crew morale may be significant.

Since the apportioned reliability of the earth landing system is 0.99994, the indication is that personal parachutes would be used, at most, in only 60 out of a million missions.

~~CONFIDENTIAL~~



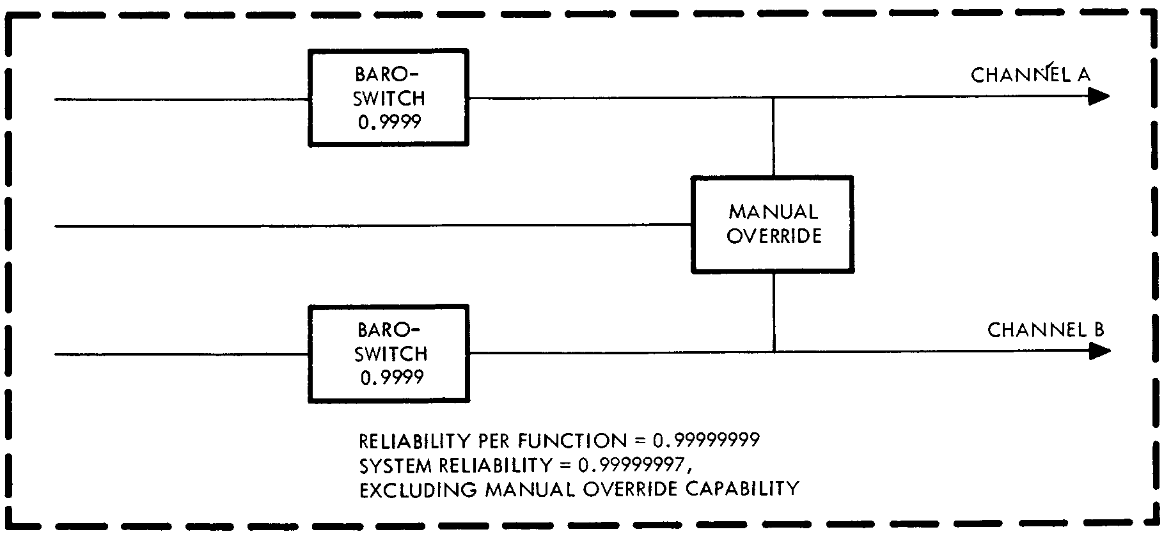


Figure 20. Baroswitch Analysis and Earth Landing Sequencer Logic Networks

The value of the personal parachutes is lessened because of the difficulties encountered with their use. These difficulties would include determining when the earth landing system had failed and that the personal parachutes were required, the crew members getting out of the spacecraft, and the fact that the spacecraft must be at sufficient altitude that personal parachutes would be effective.

The above factors, coupled with the relatively small probability of use and the weight penalty involved (approximately 150 pounds), leads to a recommendation that personal parachutes not be used. The weight involved could be used more beneficially elsewhere to increase mission- and crew-safety reliability.

EARTH LANDING SEQUENCER WIRING

A reliability evaluation was made of crossover versus noncrossover for the wiring of the earth landing sequencer. As a result of this analysis, either system is considered acceptable from a standpoint of reliability. Having crossover improves the reliability of the system a negligible amount by providing more ways of succeeding, but it is felt that the added complexity of assembly and the possible weight increase by the use of double-pole, double-throw relays, instead of single-pole, double-throw relays, do not warrant the use of this type of system.

MAIN-PARACHUTE DISCONNECT

An evaluation was made of means within the earth landing sequencer of initiating the release of the main parachutes after touchdown. The following systems were evaluated.

Impact switch and manual switch in series

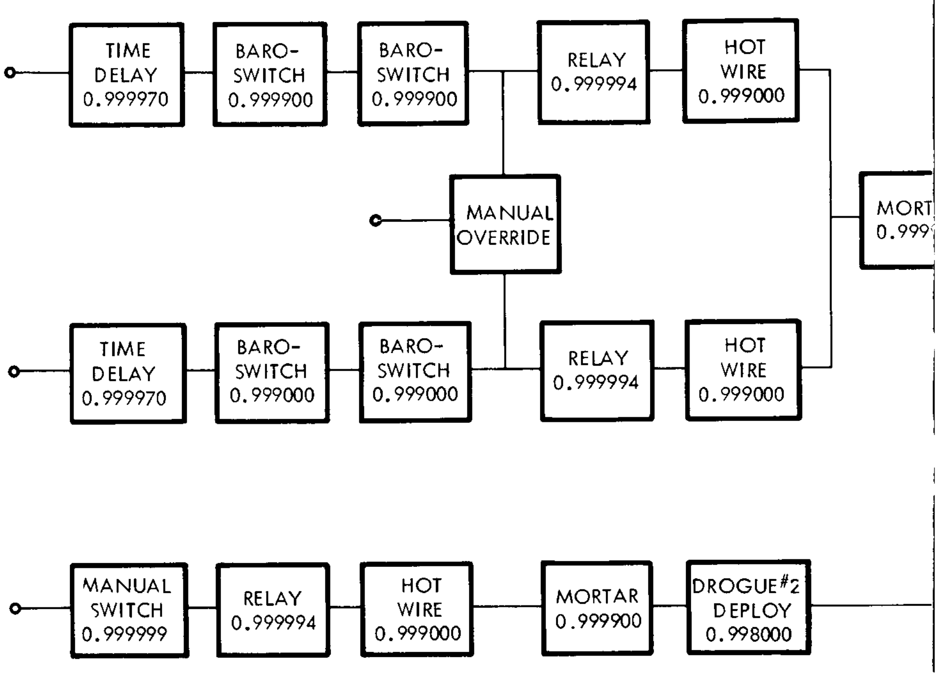
Two manual switches in series

From a reliability standpoint, both systems are acceptable.

The advantage of the impact switch and manual switch in series is that the pilot has the option of making the system either automatic or manual. When the manual switch is activated before re-entry, the system becomes automatic; when the switch is activated after touchdown, the system becomes manual. The impact-switch-and-manual-switch system guards against the opening shock of the parachutes that could cause the impact switch to close; it includes a 15-second time delay after the main chutes are deployed before the impact switch is armed.

The system with two manual switches guards against an inadvertent firing by having the two manual switches in series, but it does not have an automatic-mode capability.

~~CONFIDENTIAL~~



*TWO O
CHUTES
SUCCESS

RELIABI
(EXCLU
OVERRID

/

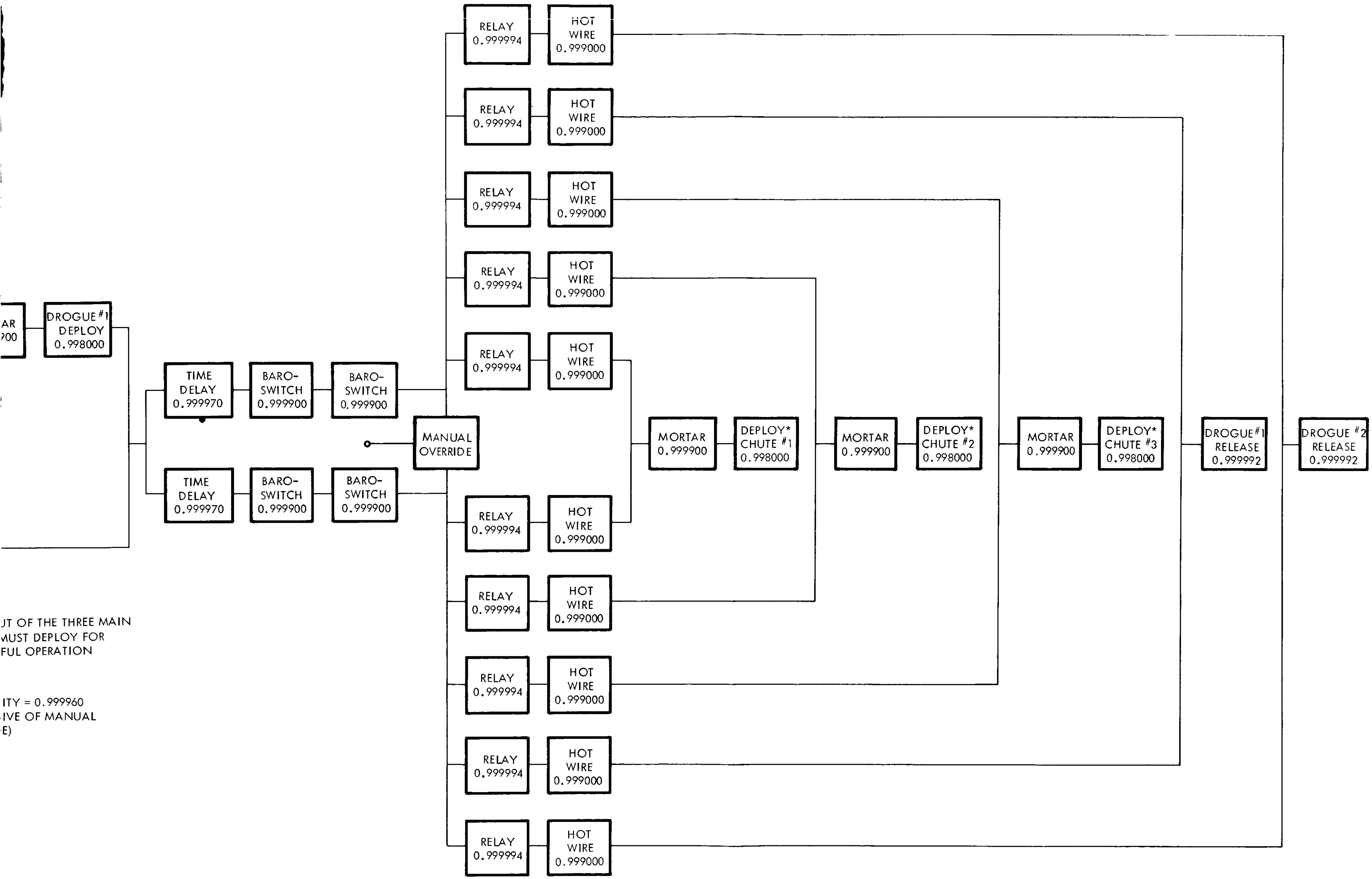


Figure 21. Parachute Deployment Logic Network

COMMAND MODULE REACTION CONTROL

APPORTIONMENT AND PREDICTION

Component allocations which satisfy the required system reliability for all of the four tentative systems are shown in Table 16. The positive expulsion tanks indicate the area for maximum reliability improvement. Since no completely satisfactory positive-expulsion system (i.e., flexible diaphragm) has been developed at this time, multiple design approaches and stringent production surveillance are necessary.

LOGIC NETWORK

Comparison of several system component configurations was completed, although a selection for Apollo has not been finalized. The logic networks and mathematical models for each system are shown in Figures 22 through 26.

[redacted]

Table 16. Command Module Reaction Control System Component Reliability Allocation

Component	Operating Time (hours)	Probability of Failure (10^{-6})* State-of-the-Art	Probability of Failure (10^{-6})* Allocated	State-of-the-Art / Allocated
Burst disk	1 cycle	17	17	1
Filter	0.75	12	12	1
Fitting**	0.75 336	0.00058 0.26	0.00058 0.26	1 1
Flow meter	0.75	39	39	1
Plug (cap)	0.75 336	0.00058 0.26	0.00058 0.26	1 1
Regulator	0.75	292	292	1
Helium tank	336	1411	100	14.1***
Positive expulsion tank	336	27900	1000	27.9***
Tubing**	0.75 336	0.00127 0.57	0.00127 0.57	1 1
Check valve	0.75	90	90	1
Fuel fill valve	336	2957	2957	1
Pressure fill valve	336	2453	2453	1
Relief valve	0.75	150	150	1
Solenoid valve (operational mode)	1 cycle	239	239	1
Solenoid valve (stand-by mode)	0.75	4	4	1
Squib valve	1 cycle	520	520	1
Vent valve	0.75	150	150	1
Rocket engines fuel valve oxidizer valve injector thrust chamber		4000	520	7.7

Note: *Not failure rates, these values are peculiar to command module reaction control system operating times and environment.

**Conditions

Component must be designed for a strength-to-load ratio of 3.5-to-1.

These values assume 100 percent inspection, and 100 percent detection of faulty or damaged components.

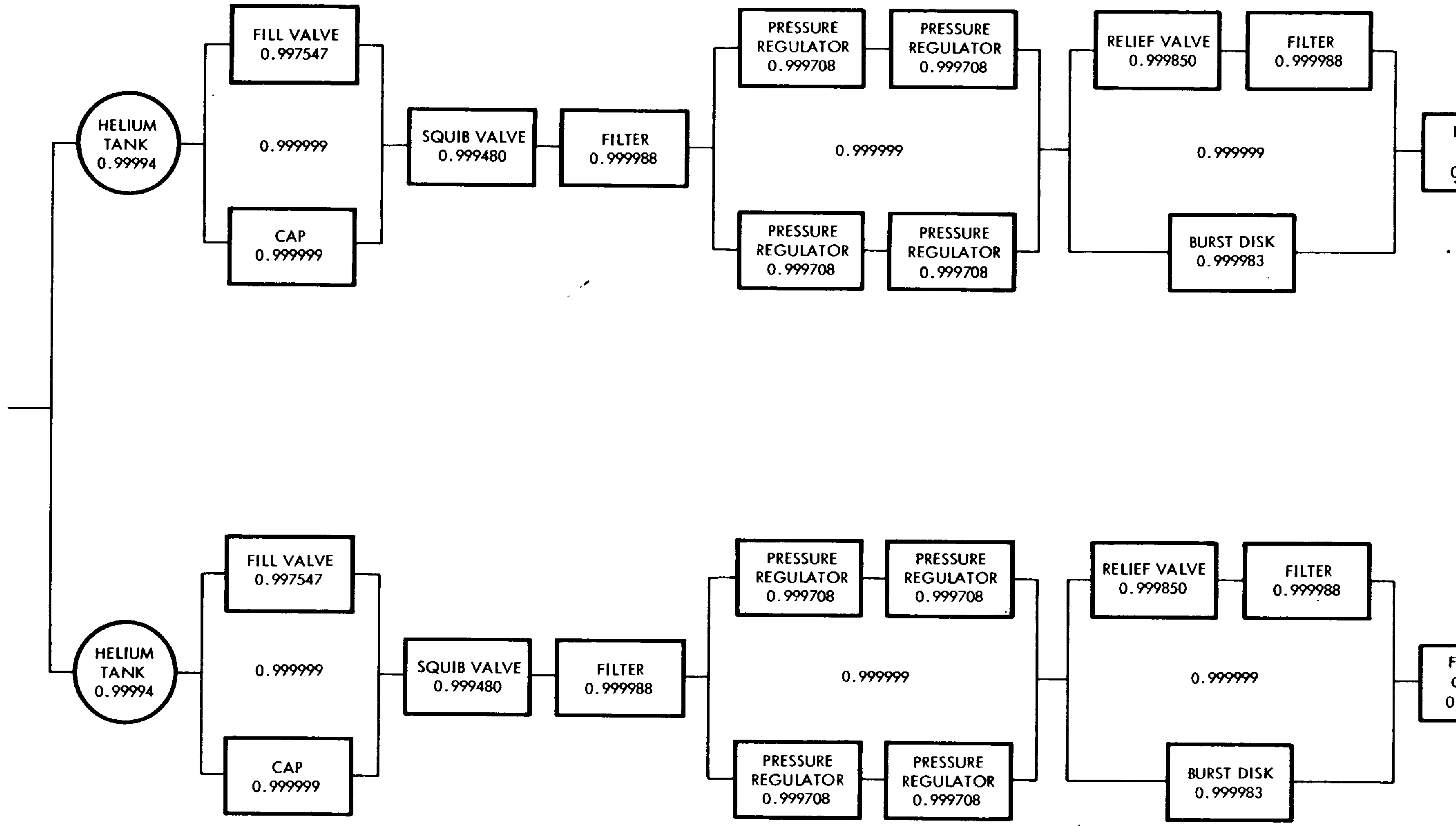
***Method of improvement

Highly selective quality control and inspection (e.g., excess-pressure acceptance testing, x-ray, and sonic inspection

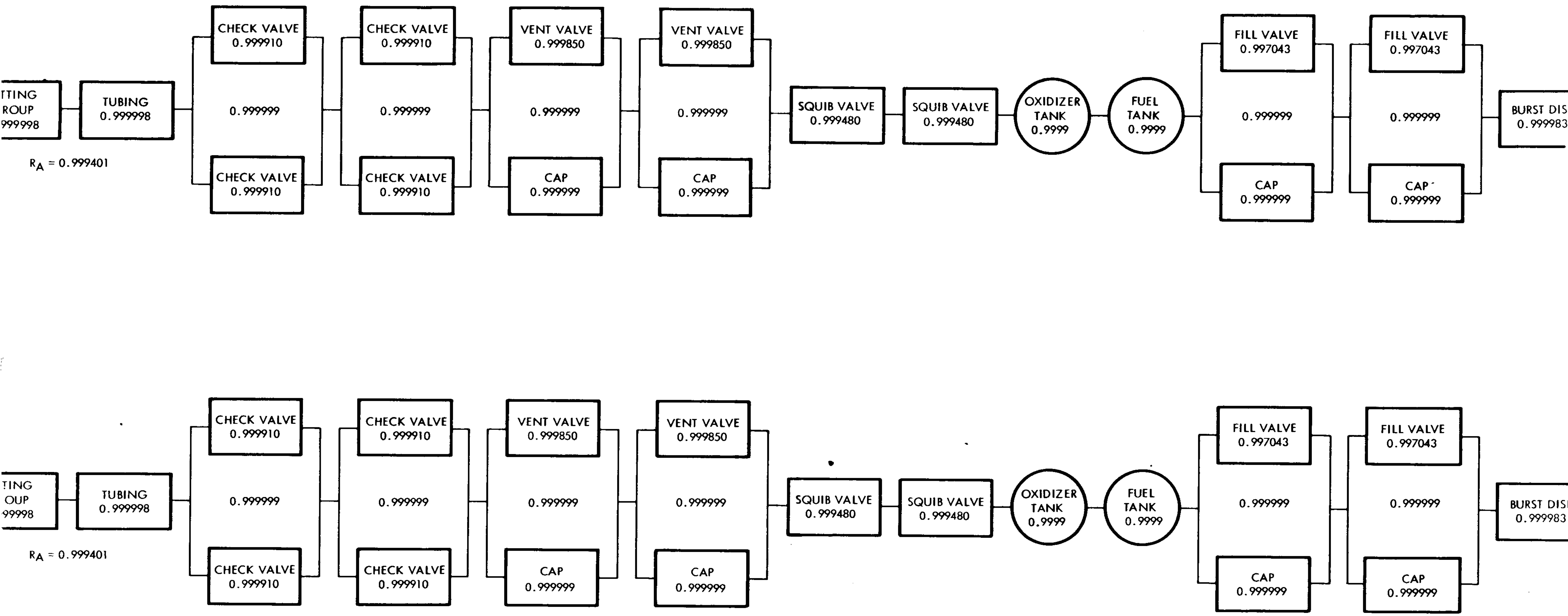
Extensive development program for expulsion device (e.g., determine to a high degree of accuracy the endurance, compatibility for an extended interaction, effects on the physical characteristics due to length, and the degree of interaction).

~~CONFIDENTIAL~~

A. PRESSURIZATION

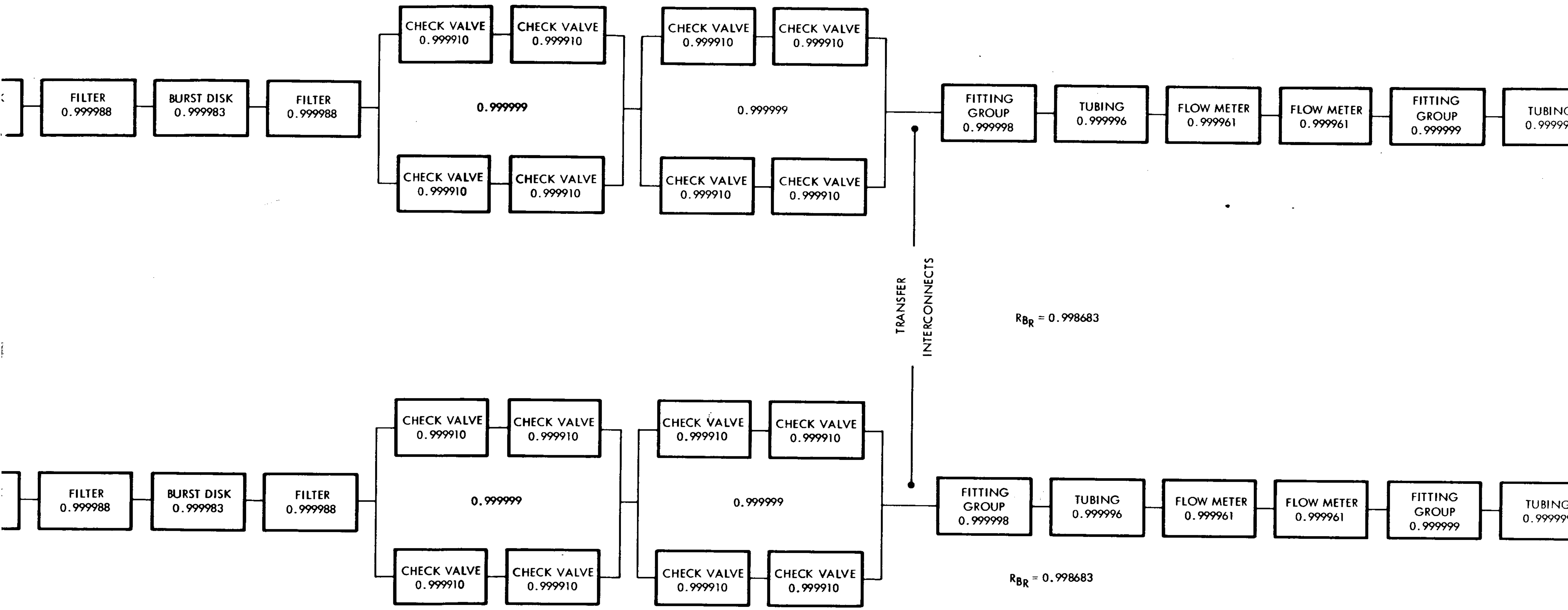


B_R REACTANT SUPPLY

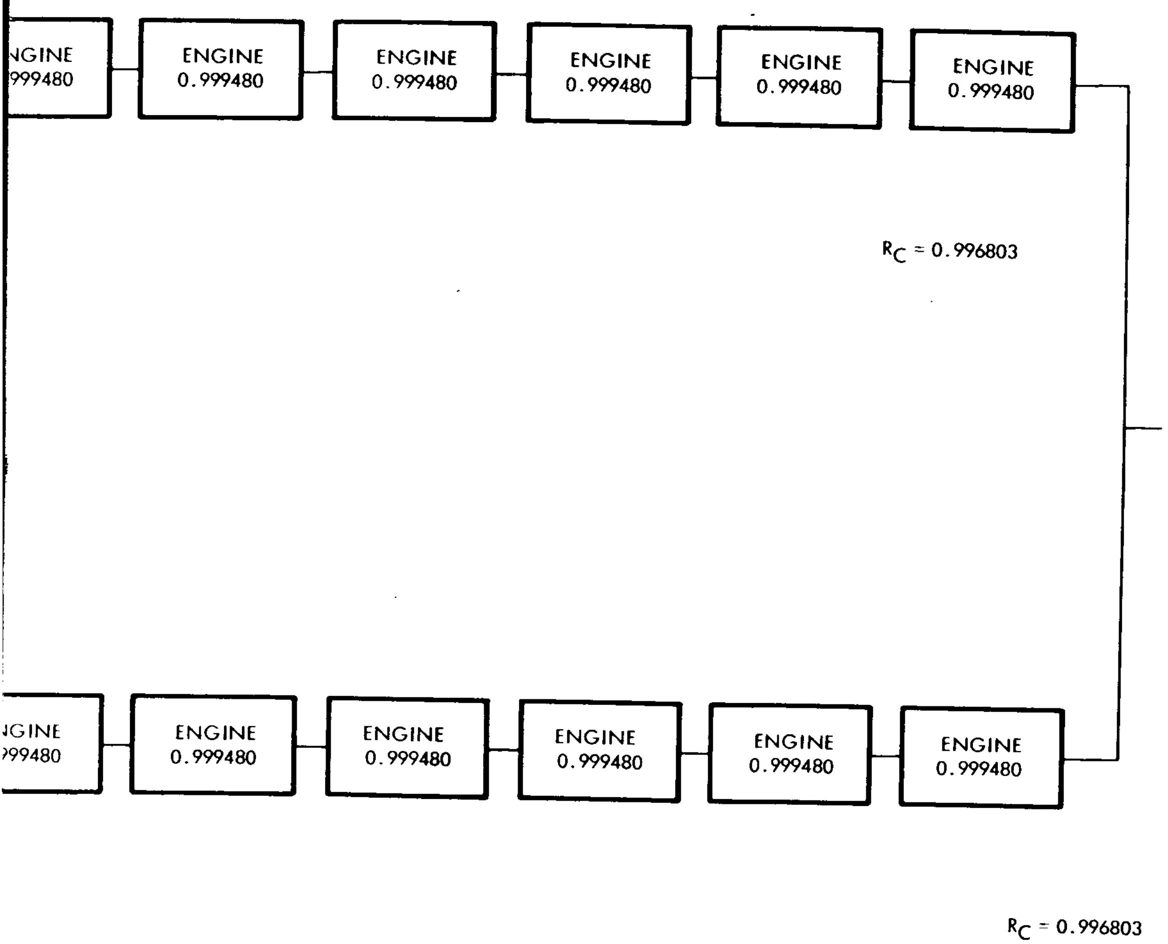


2

C. ENGINE PACKAGE



3



MATHEMATICAL MODEL FOR COMMAND MODULE REACTION CONTROL SYSTEM, DUAL-1

$$\text{RELIABILITY} = (R_A \cdot R_B \cdot R_C)^2 + 2\,(R_A^2 \cdot R_B^2 \cdot R_C q_C R_{VO}) + 2(R_A \cdot R_B \cdot q_{AB} \cdot R_C^2\, R_{VO}) + 2\,(R_A \cdot R_B \cdot q_C \cdot q_{AB} \cdot R_C \cdot R_{VO}^2)$$

IN WHICH

$R_A = 0.999402$, $R_B = 0.999208$, $R_C = 0.996803$, $R_{VO} = 0.999522$,

$q_A = 0.000598$, $q_B = 0.000792$, $q_C = 0.003197$, $q_{AB} = q_A + q_B - q_A \cdot q_B = 0.001390$,

$(R_A \cdot R_B \cdot R_C) = 0.995417$,

$$R_{(D-1)} = (0.995417)^2 + 2(0.995417)(0.996803)(0.003197)(0.999761)^2 + 2\,(0.995417)(0.001390)(0.003197)(0.999761)^2 + 2(0.995417)(0.003197)(0.001390)(0.999522)^2 + 2(0.995417)(0.999402)(0.999208)(0.003197)(0.999522) = 0.999984$$

DEFINITIONS:

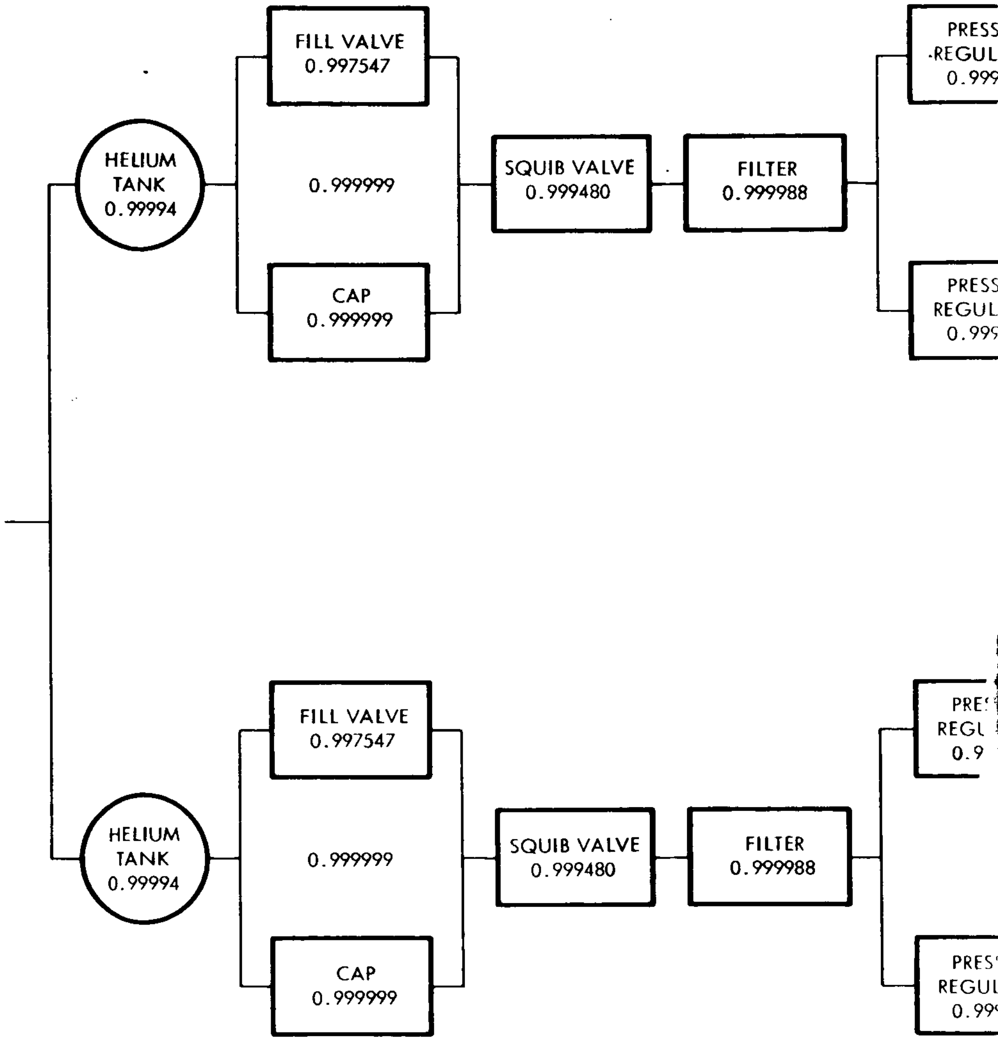
R_A = RELIABILITY OF HELIUM PRESSURIZATION SUBSYSTEM
R_B = RELIABILITY OF PROPELLANT SUBSYSTEM
R'_B = RELIABILITY OF REDUNDANT PROPELLANT SUBSYSTEM
R_C = RELIABILITY OF ENGINE SUBSYSTEM
R_{VO} = RELIABILITY OF SOLENOID VALVE OPERATION—2 VALVES
R_{SV} = RELIABILITY OF SOLENOID VALVE OPERATION ONLY
q_A = PROBABILITY OF SUBSYSTEM A FAILING
q_B = PROBABILITY OF SUBSYSTEM B FAILING
q_C = PROBABILITY OF SUBSYSTEM C FAILING

4

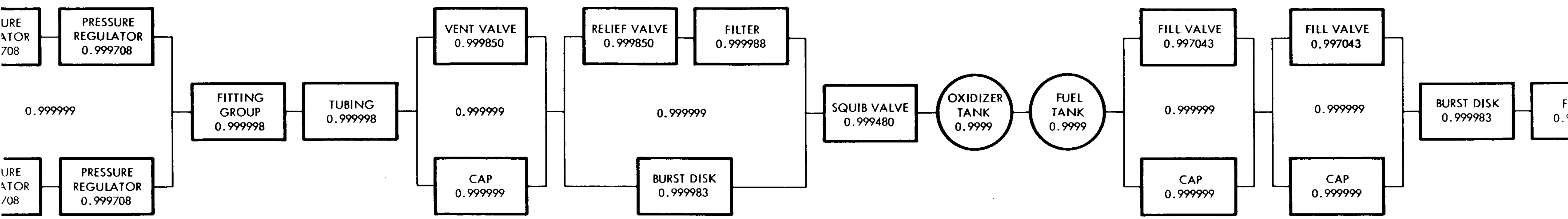
Figure 23. Command Module Dual 1 Reaction Control System Logic Network and Mathematical Model

[redacted]

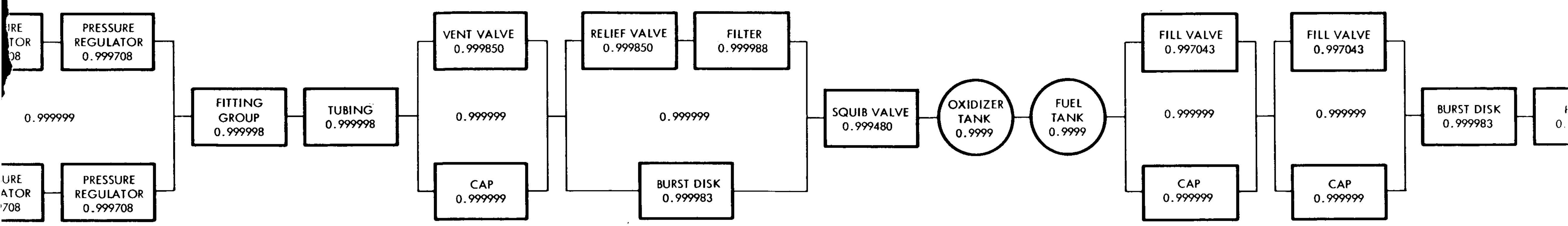
A. PRESSURIZATION



B. REACTANT SUPPLY

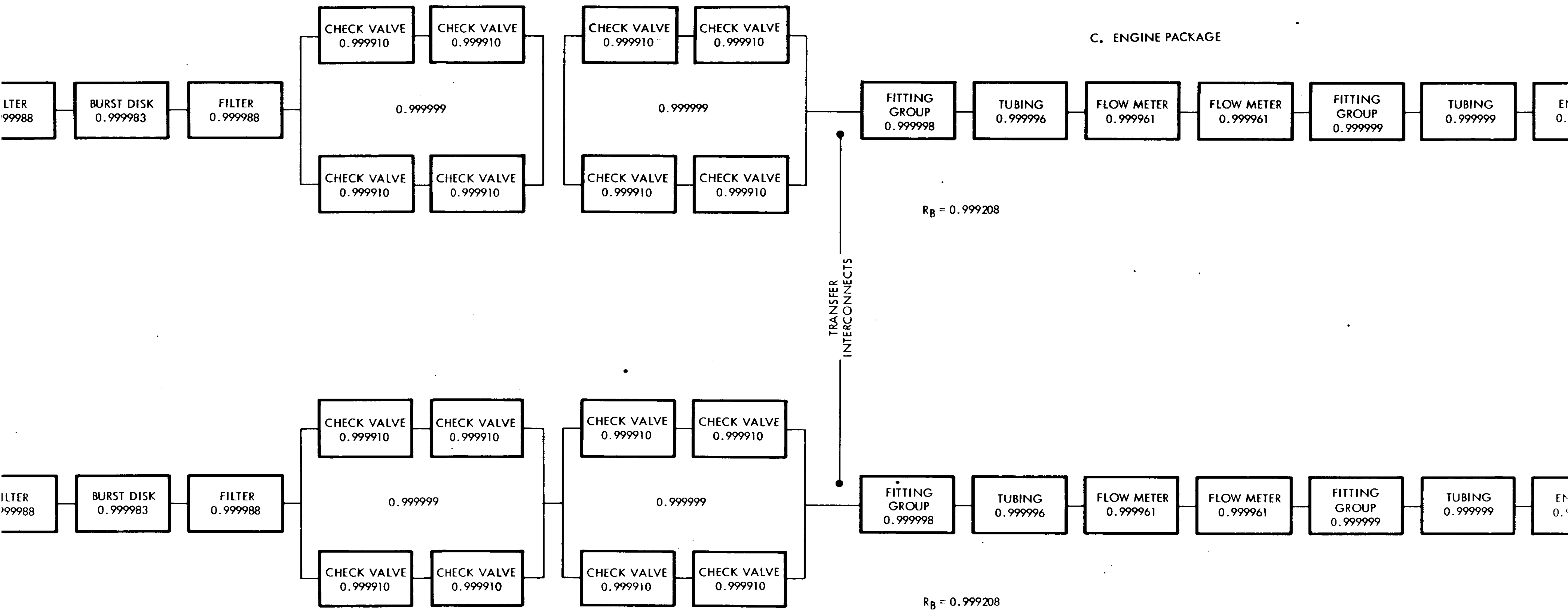


$R_A = 0.999402$

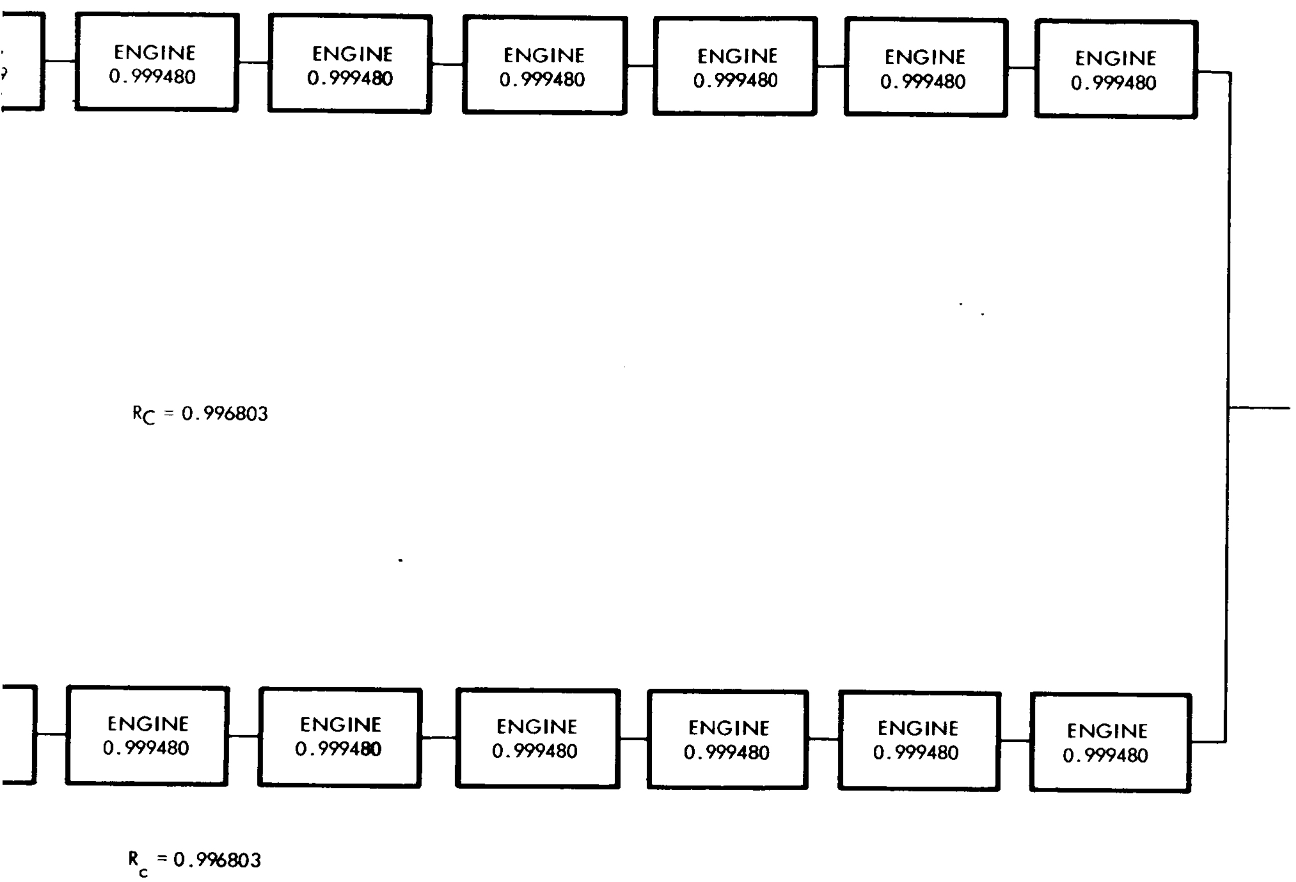


$R_A = 0.999402$

2


C. ENGINE PACKAGE
LTER
99988
BURST DISK
0.999983
FILTER
0.999988
CHECK VALVE
0.999910
0.999999
FITTING GROUP
0.999998
TUBING
0.999996
FLOW METER
0.999961
FITTING GROUP
0.999999
TUBING
0.999999
R_B = 0.999208
TRANSFER INTERCONNECTS

3



MATHEMATICAL MODEL OF COMMAND MODULE REACTION CONTROL SYSTEM, DUAL-R

$$\text{RELIABILITY} = R_A^{2}R_B^{2}R_C^{2} + 2\left[R_A^{2}R_B^{2}R_C q_C R_{VO}\right] + 2\left[R_A R_B q_{AB} R_C^{2} R_{VO}\right]$$

$$+2\left[R_A R_B R_C q_{AB} q_C R_{VO}\right] + 2\left[R_A R_B q_C q_{AB} R_C R_{VO}^{2}\right]$$

IN WHICH:

$R_A = 0.999401$, $R_B = 0.998683$, $R_C = 0.996803$,

$q_A = 0.000599$, $q_B = 0.001317$, $q_C = 0.003197$,

$R_{VO} = 0.999522$, AND $q_{AB} = q_A + q_B - q_A \cdot q_B = 0.001915$

$$R_{(R)} = (0.999401)^2 (0.998683)^2 (0.996803)^2 + 2\left[(0.999401)^2 (0.998683)^2 (0.996803)(0.003197)(0.999522)\right]$$

$$+2\left[(0.999401)(0.998683)(0.996803)(.001915)(0.003197)(0.999522)\right] + 2\left[(0.999401)(0.998683)\right.$$

$$\left.(0.003197)(0.001915)(0.996803)(0.999522)^2\right] + 2\left[(0.999401)(0.998683)(0.996803)^2(0.001915)(0.999522)\right]$$

$$= 0.999979$$

DEFINITIONS

R_A = RELIABILITY OF HELIUM PRESSURIZATION SUBSYSTEM
R_B = RELIABILITY OF PROPELLANT SUBSYSTEM
R'_B = RELIABILITY OF REDUNDANT PROPELLANT SUBSYSTEM
R_C = RELIABILITY OF ENGINE SUBSYSTEM
R_{VO} = RELIABILITY OF SOLENOID VALVE OPERATION - 2 VALVES
R_{SV} = RELIABILITY OF SOLENOID VALVE OPERATION ONLY
q_A = PROBABILITY OF SUBSYSTEM A FAILING
q_B = PROBABILITY OF SUBSYSTEM B FAILING
q_C = PROBABILITY OF SUBSYSTEM C FAILING

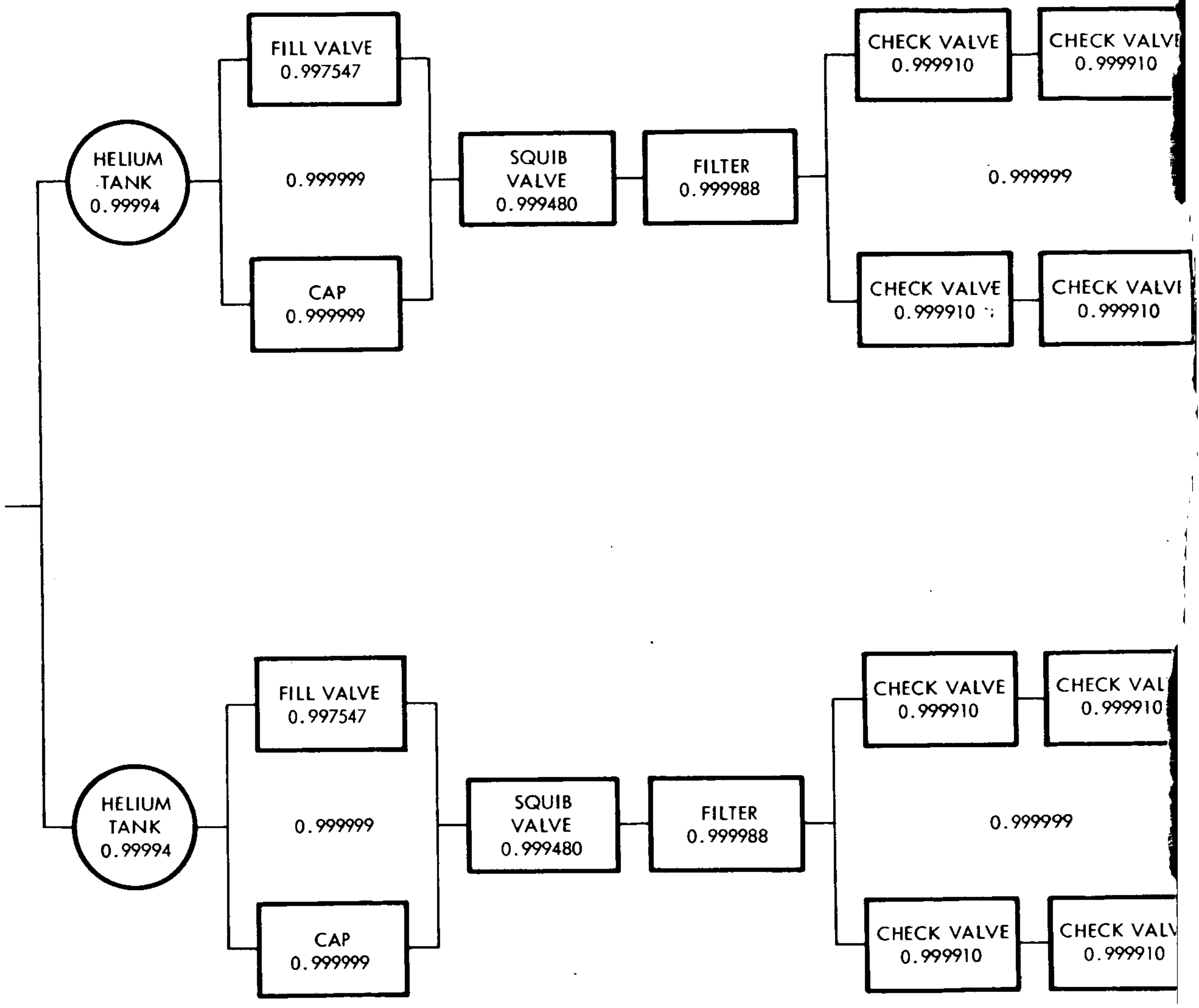
Figure 22. Command Module Dual R Reaction Control System Logic Network and Mathematical Model

4

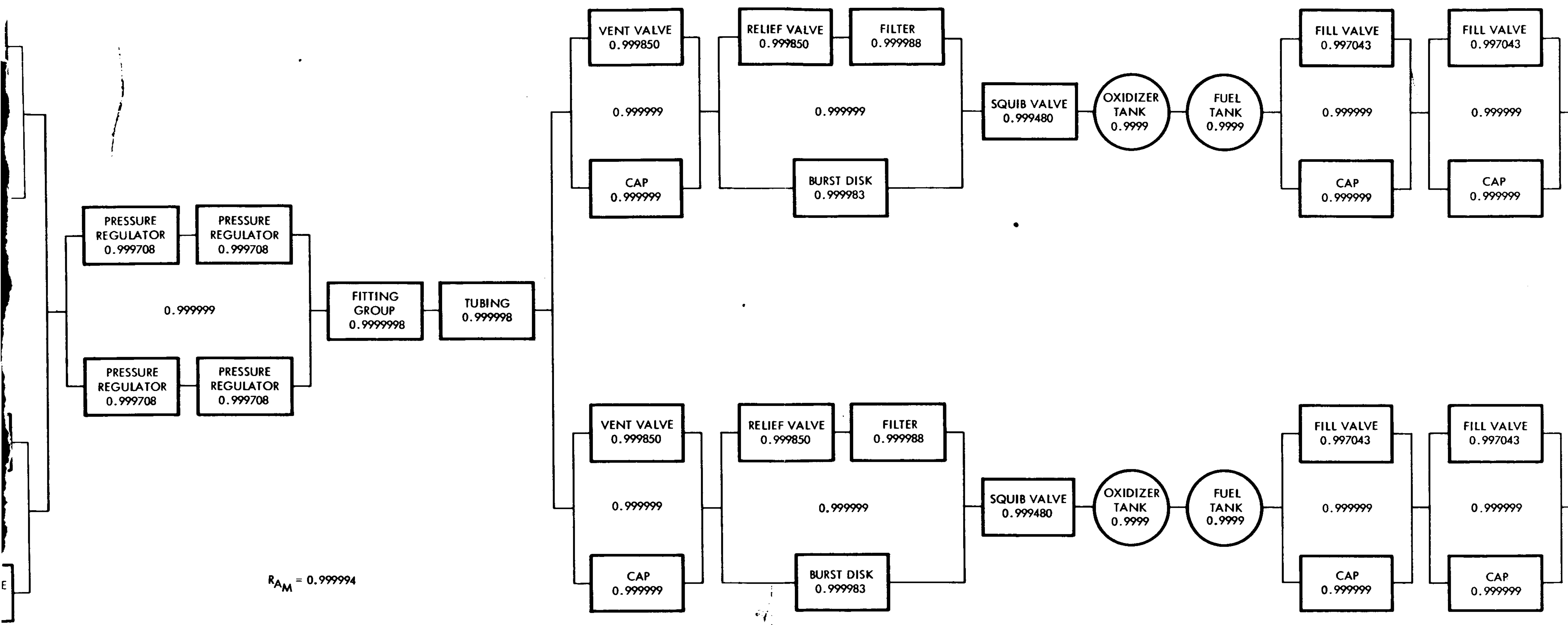
~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

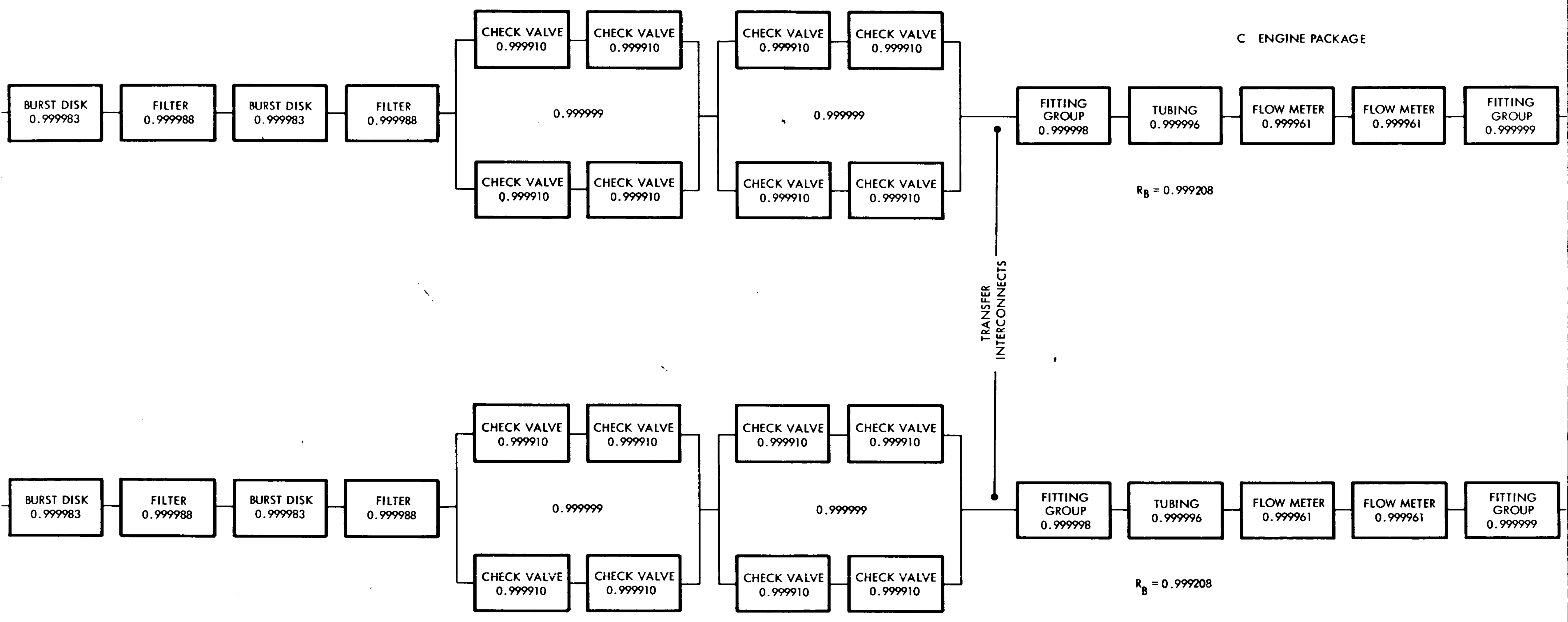
A_M PRESSURIZATION (MODIFIED)



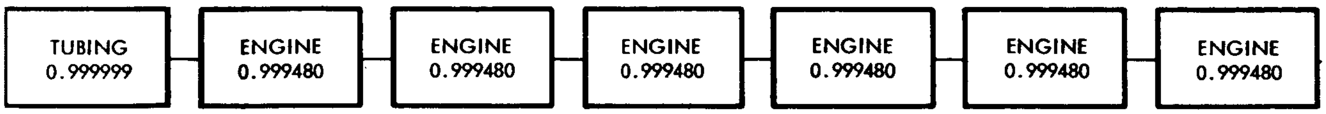
B REACTANT SUPPLY



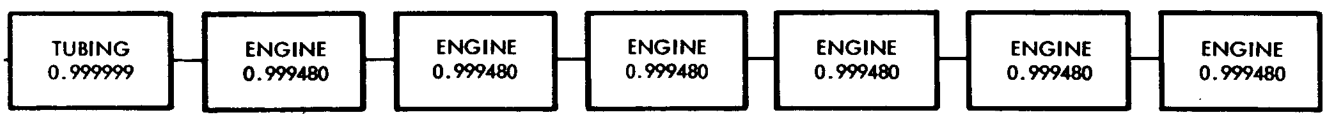
2


C ENGINE PACKAGE
BURST DISK 0.999983
FILTER 0.999988
BURST DISK 0.999983
FILTER 0.999988
CHECK VALVE 0.999910
0.999999
FITTING GROUP 0.999998
TUBING 0.999996
FLOW METER 0.999961
FLOW METER 0.999961
FITTING GROUP 0.999999
$R_B = 0.999208$
TRANSFER INTERCONNECTS

3



$R_C = 0.996803$



$R_C = 0.996803$

MATHEMATICAL MODEL FOR COMMAND MODULE REACTION CONTROL SYSTEM, DUAL-2

$$\text{RELIABILITY} = R_A \Big(R_B^2 \cdot R_C^2 + 2\,R_B^2 R_C q_C R_{VO} + 2 q_B R_B R_{VO} R_{SV} R_C^2 + 2 R_B R_C q_B q_C R_{VO} R_{SV} + 2 R_B q_C R_{SV} R_{VO}^2 q_B R_C \Big)$$

IN WHICH

$R_A = 0.999994$, $R_B = 0.999208$, $R_C = 0.996803$,

$R_{VO} = 0.999522$, $R_{SV} = 0.999761$, $q_B = 0.000792$, and $q_C = 0.003197$

$$R_{(D-2)} = (0.999994) \Big[(0.999208)^2 (0.996802)^2 + 2(0.999208)^2 (0.996803)(.003197)(0.999522) + 2 (0.000792)(0.999208)(0.999522)(0.999761)(0.996803)^2 + 2(0.999208)(0.996803) (0.00792)(0.003197)(0.999522)(0.999761) + 2(0.999208)(0.000792)(0.999761)(0.999522)^2 (0.000792)(0.996803) \Big]$$

$$= \underline{0.999979}$$

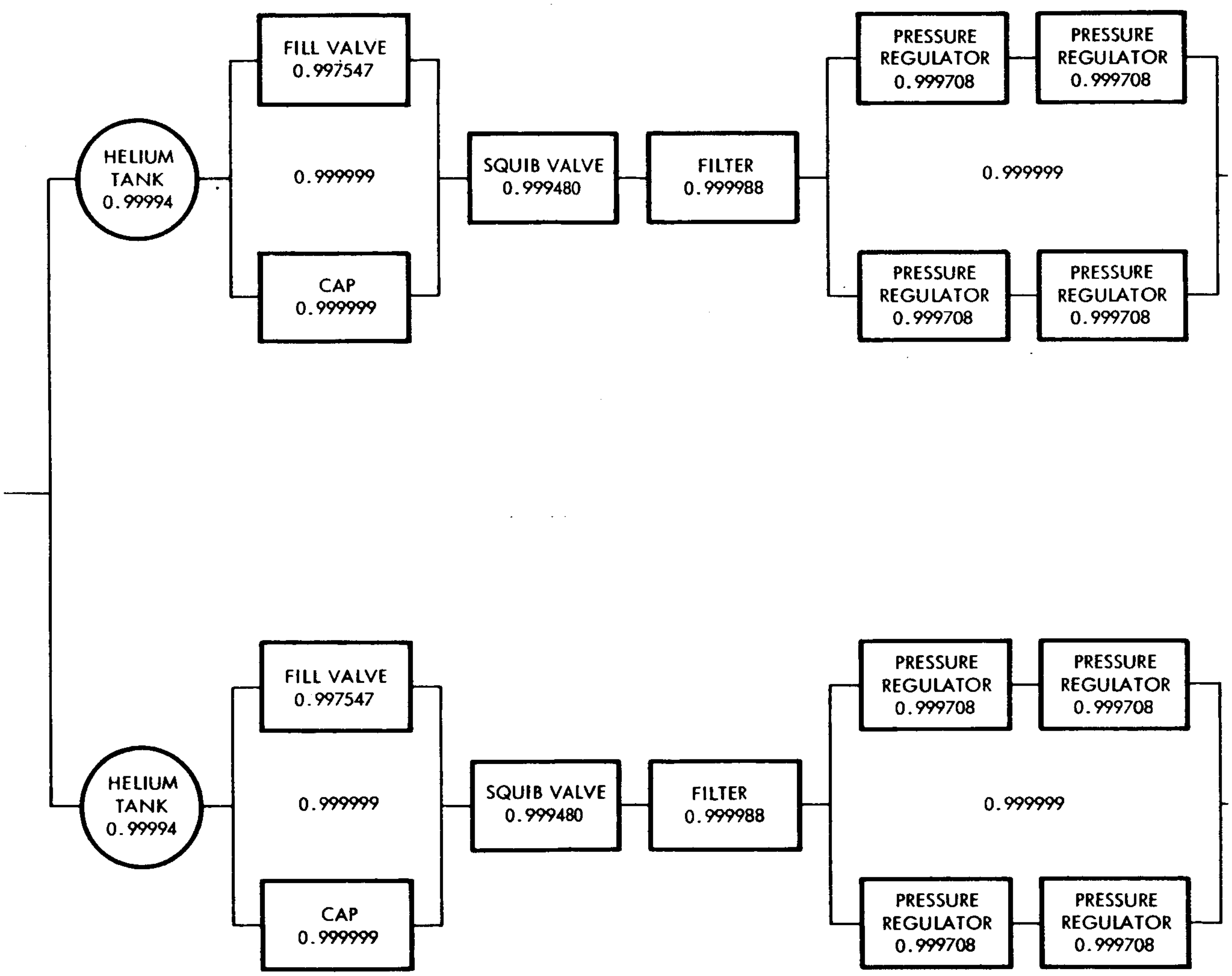
DEFINITIONS:

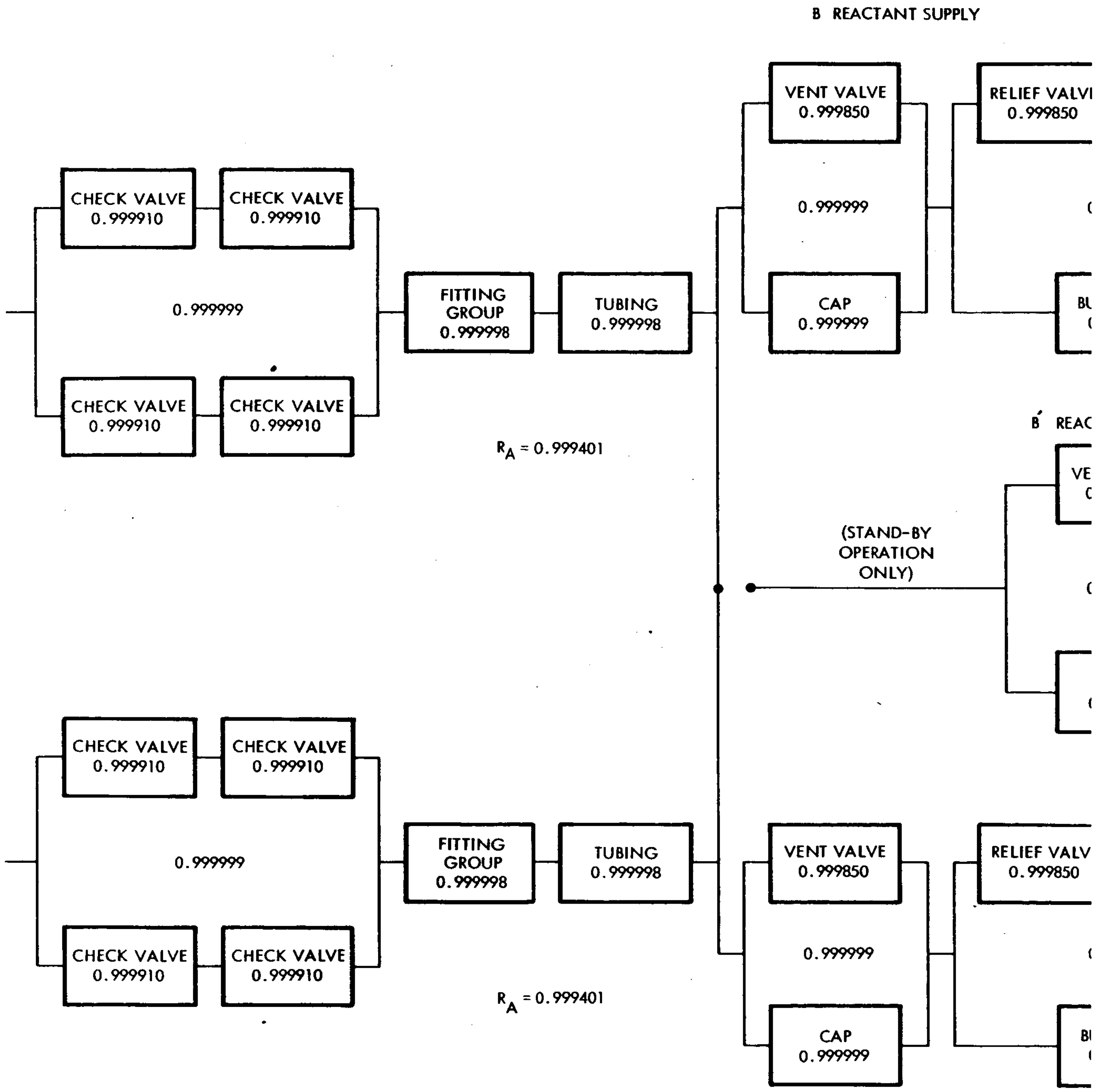
R_A = RELIABILITY OF HELIUM PRESSURIZATION SUBSYSTEM
R_B = RELIABILITY OF PROPELLANT SUBSYSTEM
R'_B = RELIABILITY OF REDUNDANT PROPELLANT SUBSYSTEM
R_C = RELIABILITY OF ENGINE SUBSYSTEM
R_{VO} = RELIABILITY OF SOLENOID VALVE OPERATION - 2 VALVES
R_{SV} = RELIABILITY OF SOLENOID VALVE OPERATION ONLY
q_A = PROBABILITY OF SUBSYSTEM A FAILING
q_B = PROBABILITY OF SUBSYSTEM B FAILING
q_C = PROBABILITY OF SUBSYSTEM C FAILING

Figure 24. Command Module Dual 2 Reaction Control System Logic Network and Mathematical Model

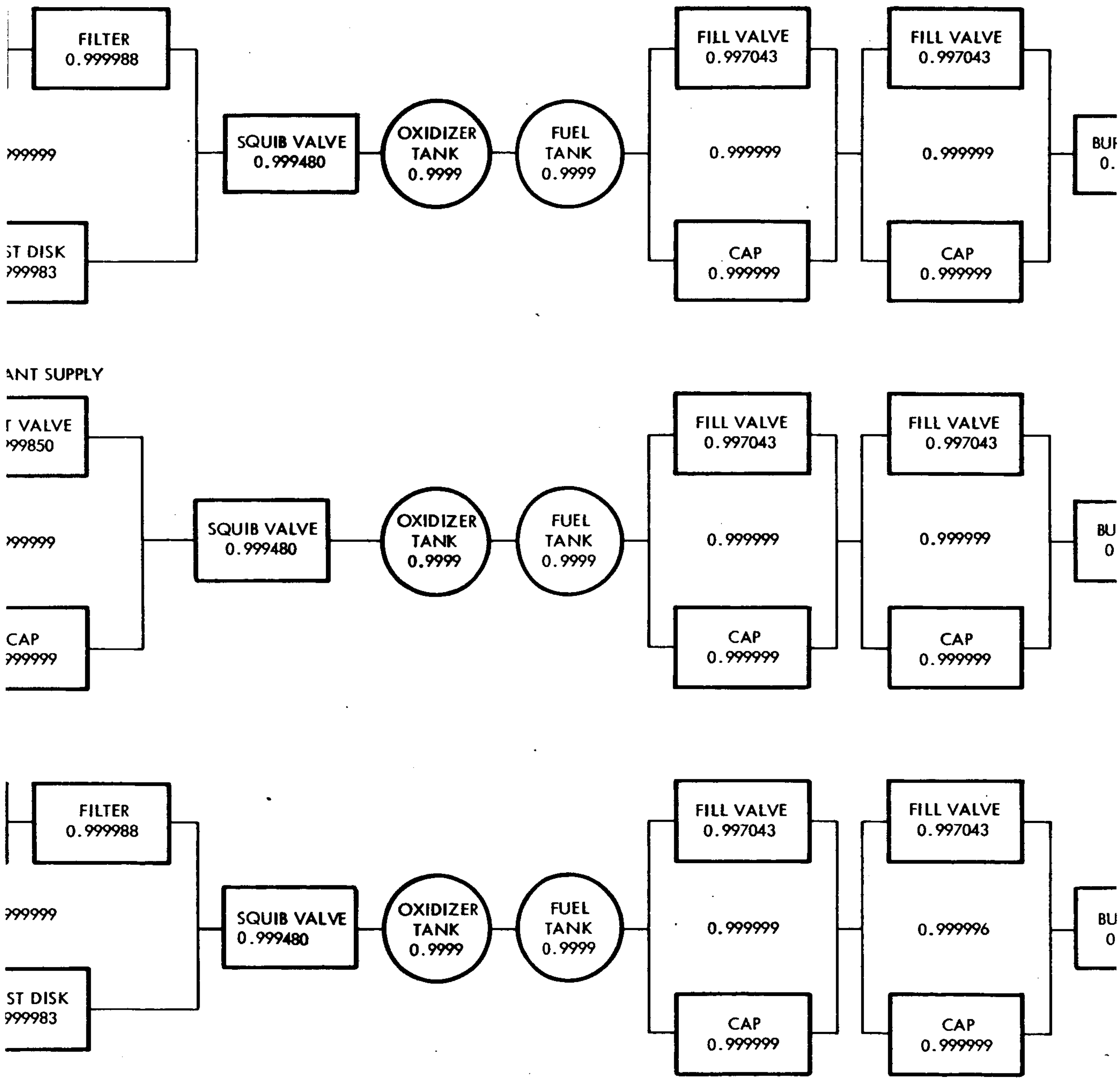
~~FIDENTIAL~~

A PRESSURIZATION

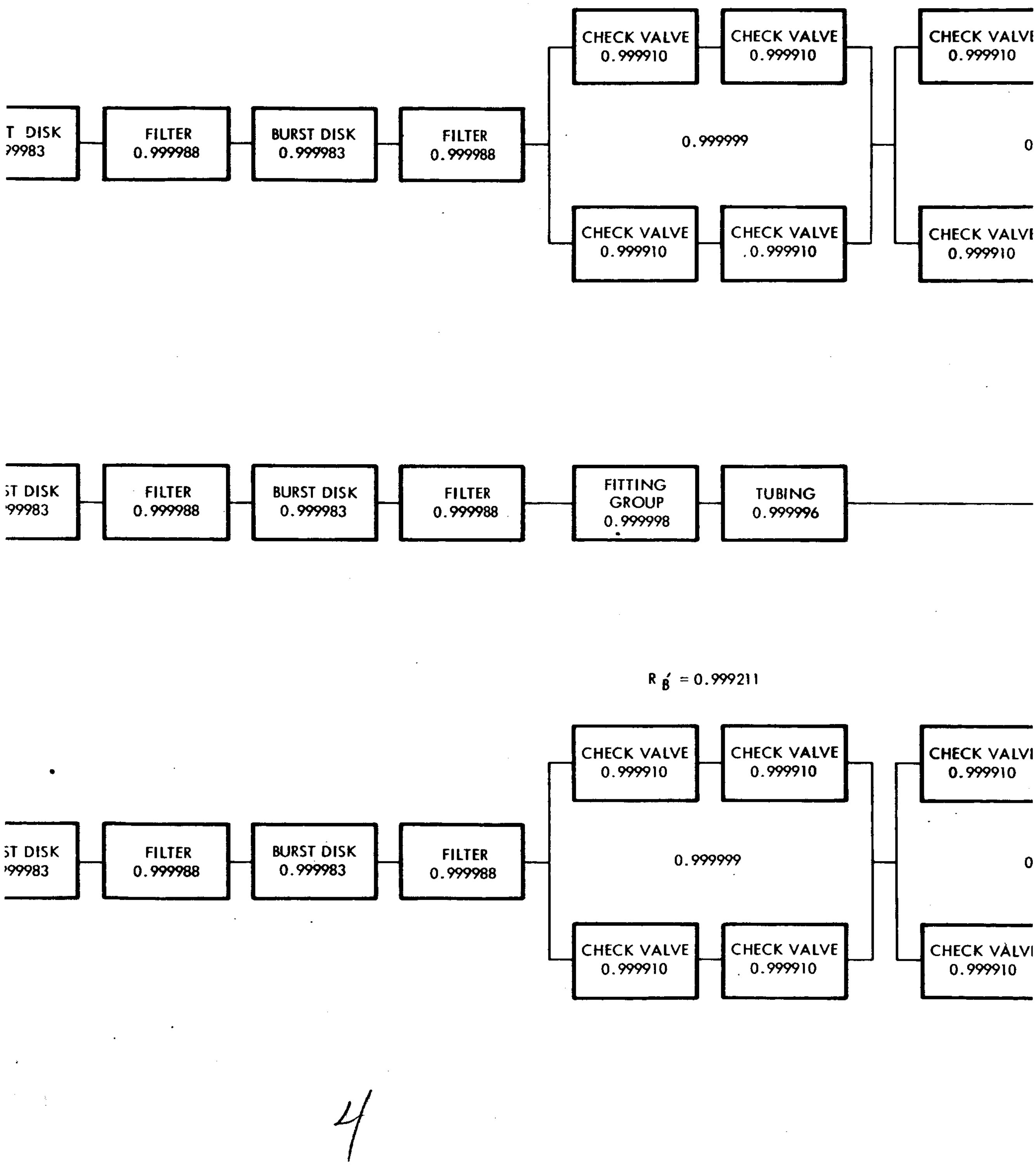



B REACTANT SUPPLY
VENT VALVE 0.999850
RELIEF VALVE 0.999850
CHECK VALVE 0.999910
CHECK VALVE 0.999910
0.999999
0.999999
FITTING GROUP 0.999998
TUBING 0.999998
CAP 0.999999
CHECK VALVE 0.999910
CHECK VALVE 0.999910
R_A = 0.999401
B' REAC
VE
(STAND-BY OPERATION ONLY)
CHECK VALVE 0.999910
CHECK VALVE 0.999910
0.999999
FITTING GROUP 0.999998
TUBING 0.999998
VENT VALVE 0.999850
RELIEF VALV 0.999850
0.999999
CHECK VALVE 0.999910
CHECK VALVE 0.999910
R_A = 0.999401
CAP 0.999999

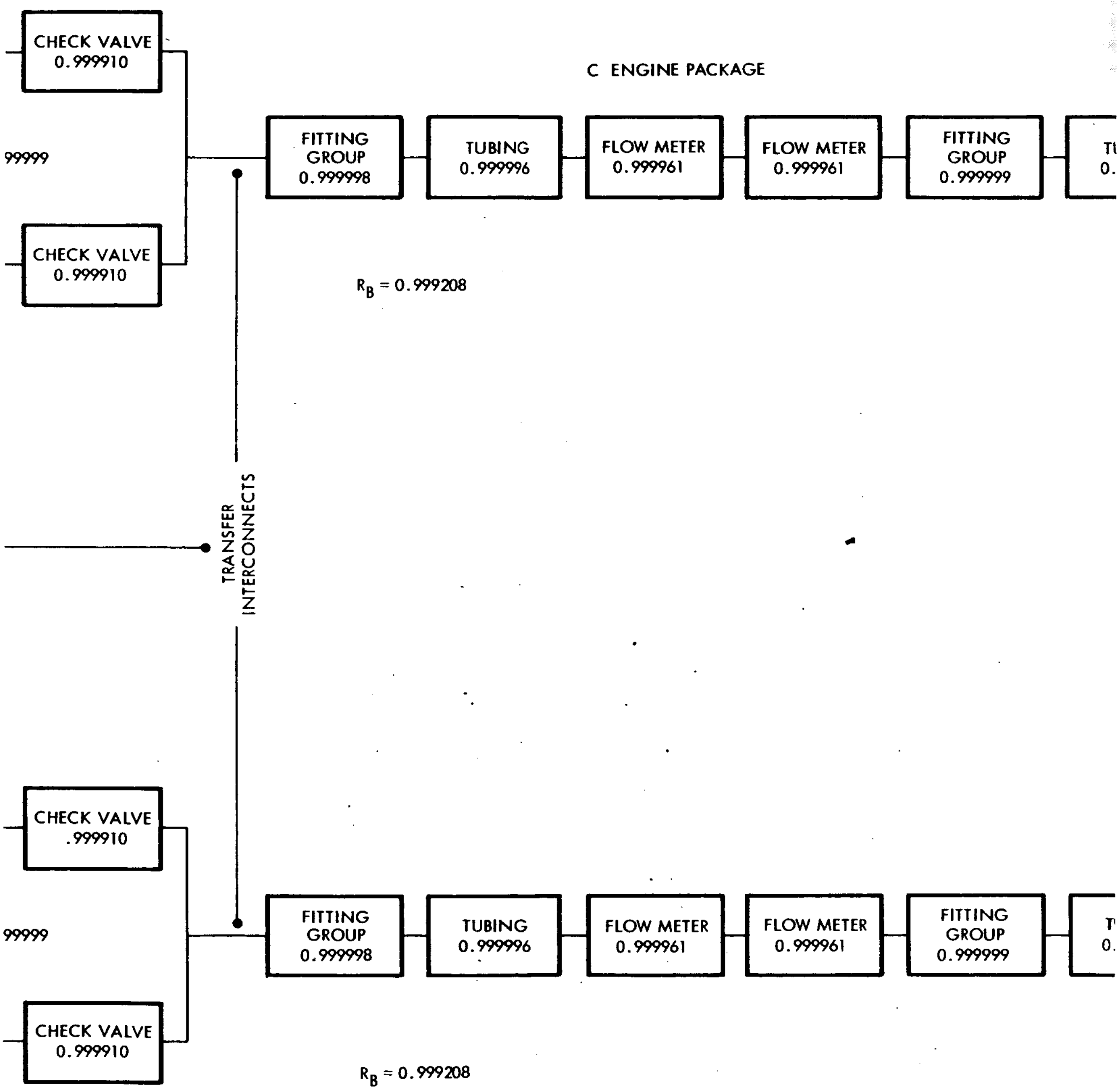
2



FILTER
0.999988
SQUIB VALVE
0.999480
OXIDIZER TANK
0.9999
FUEL TANK
0.9999
FILL VALVE
0.997043
0.999999
CAP
0.999999
FILL VALVE
0.997043
0.999999
CAP
0.999999
ANT SUPPLY
SQUIB VALVE
0.999480
OXIDIZER TANK
0.9999
FUEL TANK
0.9999
FILL VALVE
0.997043
0.999999
CAP
0.999999
FILL VALVE
0.997043
0.999999
CAP
0.999999
FILTER
0.999988
SQUIB VALVE
0.999480
OXIDIZER TANK
0.9999
FUEL TANK
0.9999
FILL VALVE
0.997043
0.999999
CAP
0.999999
FILL VALVE
0.997043
0.999996
CAP
0.999999

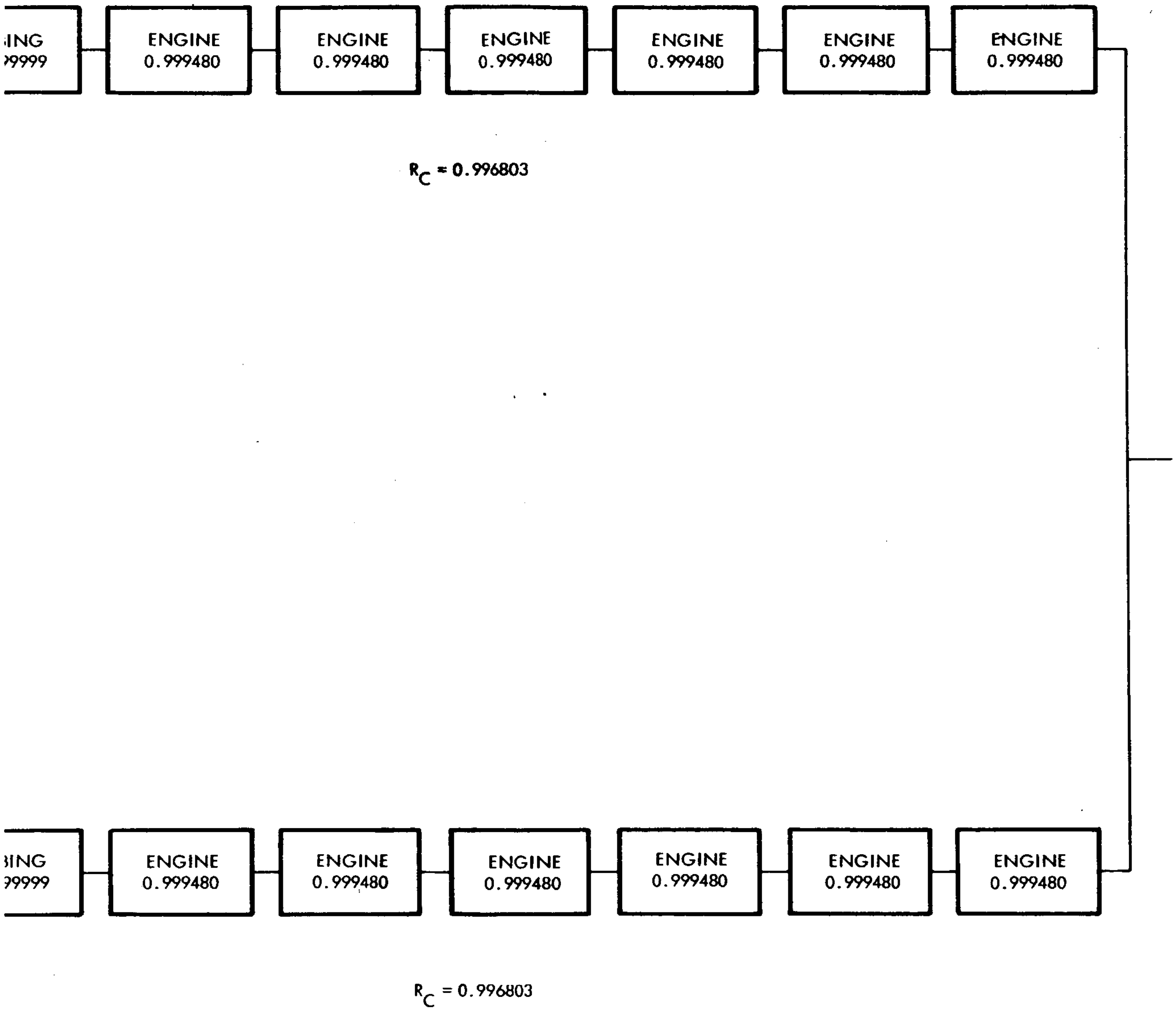


T DISK
?99983
FILTER
0.999988
BURST DISK
0.999983
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0
ST DISK
?99983
FILTER
0.999988
BURST DISK
0.999983
FILTER
0.999988
FITTING
GROUP
0.999998
TUBING
0.999996
$R_B' = 0.999211$
ST DISK
?99983
FILTER
0.999988
BURST DISK
0.999983
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0
4



C ENGINE PACKAGE
CHECK VALVE 0.999910
99999
CHECK VALVE 0.999910
FITTING GROUP 0.999998
TUBING 0.999996
FLOW METER 0.999961
FLOW METER 0.999961
FITTING GROUP 0.999999
R_B = 0.999208
TRANSFER INTERCONNECTS
CHECK VALVE .999910
99999
CHECK VALVE 0.999910
FITTING GROUP 0.999998
TUBING 0.999996
FLOW METER 0.999961
FLOW METER 0.999961
FITTING GROUP 0.999999
R_B = 0.999208

5


ING
99999
ENGINE
0.999480
ENGINE
0.999480
ENGINE
0.999480
ENGINE
0.999480
ENGINE
0.999480
ENGINE
0.999480
R_C = 0.996803
ING
99999
ENGINE
0.999480
ENGINE
0.999480
ENGINE
0.999480
ENGINE
0.999480
ENGINE
0.999480
ENGINE
0.999480
R_C = 0.996803

6

MATHEMATICAL MODEL FOR COMMAND MODULE REACTION CONTROL SYSTEM, TRIPLE-2

$$\begin{aligned}\text{RELIABILITY} = {} & R_A^2 \cdot R_B^2 \cdot R_C^2 + 2q_C R_B R_{B'} R_C R_{SV} R_{VO}^2 R_A^2 + 2q_A R_{VO} R_A R_{SV} R_B R_{B'} R_C^2 \\ & + 2q_B R_B R_{SV} R_{B'} R_{VO} R^2{}_A R_C^2 + 2q_A q_B R_{SV} R_A R_B R_{B'} R_{VO}^2 R_C^2 + 4\, q_A q_C R_A R_C \\ & R_B R_{B'} R_{SV} R_{VO}^2 + 2q_A q_B q_C R_A R_B R_C R_{B'} R_{SV} R_{VO}^2 (1 + R_{VO})\end{aligned}$$

IN WHICH

$R_A = 0.999401$, $R_B = 0.999208$, $R_C = 0.996803$, $R_{SV} = 0.999761$, $R_{VO} = 0.999522$,

$q_A = 0.000599$, $q_B = 0.000792$, $q_C = 0.003197$,

$R_{VO}^2 = 0.999044$, and $R_{B'} = 0.999211$

$$\begin{aligned}R_{(T-2)} = {} & (0.999401)^2 (0.999208)^2 (0.996803)^2 + 2(0.003197)(0.999208)(0.999211)(0.996803)(0.999761) \\ & (0.999522)^2 (0.999401)^2 + 2(0.000599)(0.999522)(0.999401)(0.999761)(0.999208)(0.999211) \\ & (0.996803)^2 + 2(0.000792)(0.999208)(0.999761)(0.999211)(0.999522)(0.999401)^2 (0.996803)^2 \\ & + 2(0.000599)(0.000792)(0.999761)(0.999401)(0.999208)(0.999211)(0.999522)^2 (0.996803)^2 \\ & + 4(0.000599)(0.003197)(0.999401)(0.996803)(0.999208)(0.999211)(0.999761)(0.999522)^2 \\ & + 2(0.000599)(0.000792)(0.003197)(0.999401)(0.999208)(0.996803)(0.999211)(0.999761)(0.999522)^2 \\ & (1.999522) = 0.999967\end{aligned}$$

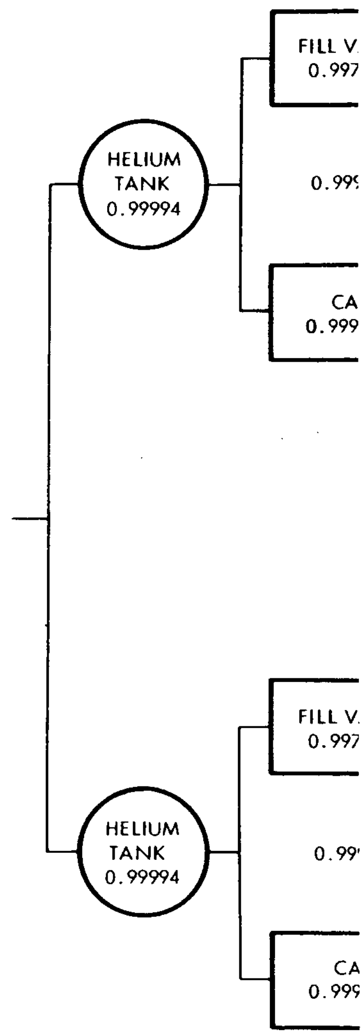
DEFINITIONS:

R_A = RELIABILITY OF HELIUM PRESSURIZATION SUBSYSTEM
R_B = RELIABILITY OF PROPELLANT SUBSYSTEM
$R_{B'}$ = RELIABILITY OF REDUNDANT PROPELLANT SUBSYSTEM
R_C = RELIABILITY OF ENGINE SUBSYSTEM
R_{VO} = RELIABILITY OF SOLENOID VALVE OPERATION - 2 VALVES
R_{SV} = RELIABILITY OF SOLENOID VALVE OPERATION ONLY
q_A = PROBABILITY OF SUBSYSTEM A FAILING
q_B = PROBABILITY OF SUBSYSTEM B FAILING
q_C = PROBABILITY OF SUBSYSTEM C FAILING

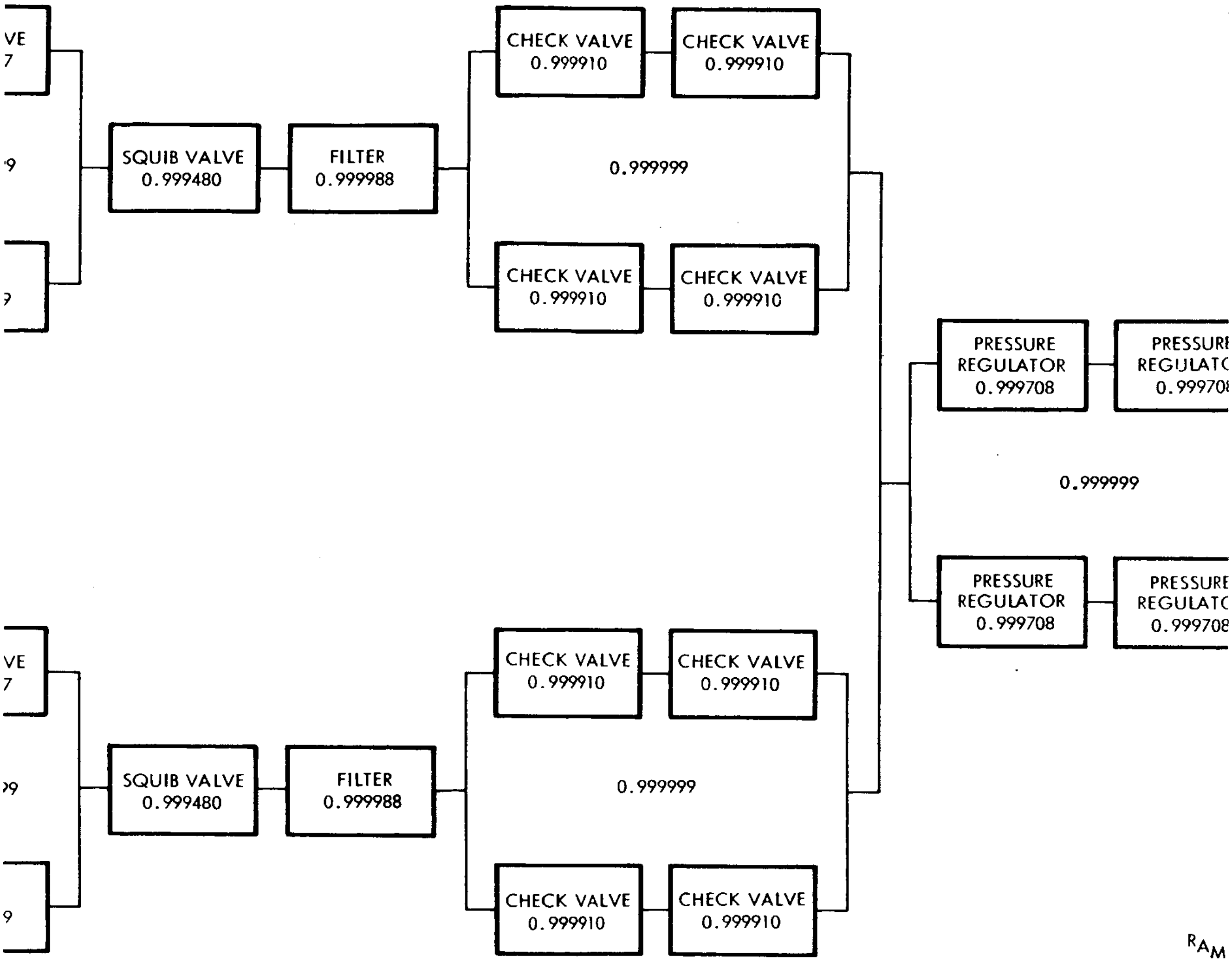
Figure 25. Command Module Triple 2 Reaction Control System Logic Network and Mathematical Model

~~CONFIDENTIAL~~

A_M PRESSURIZATI

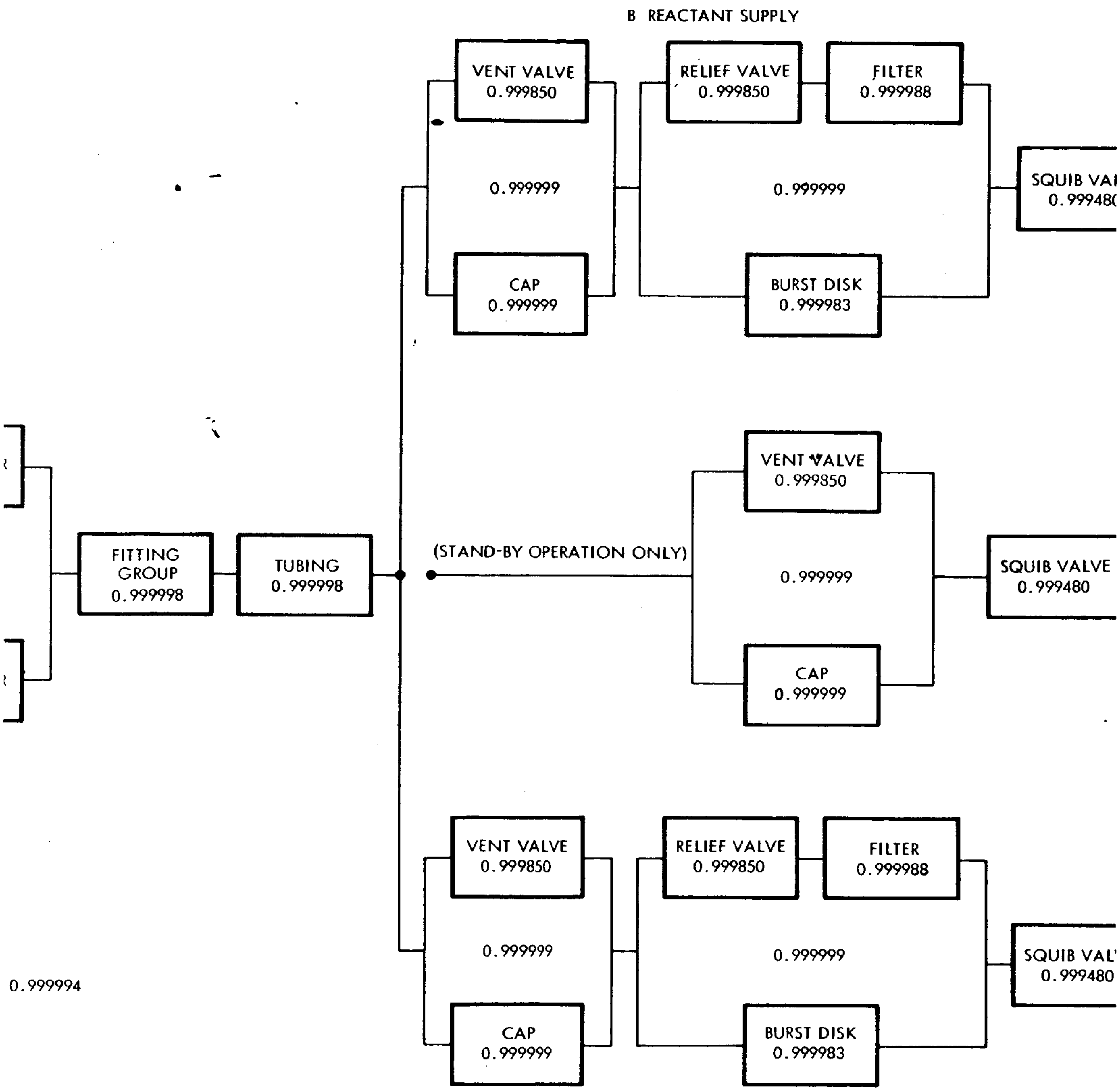


N (MODIFIED)

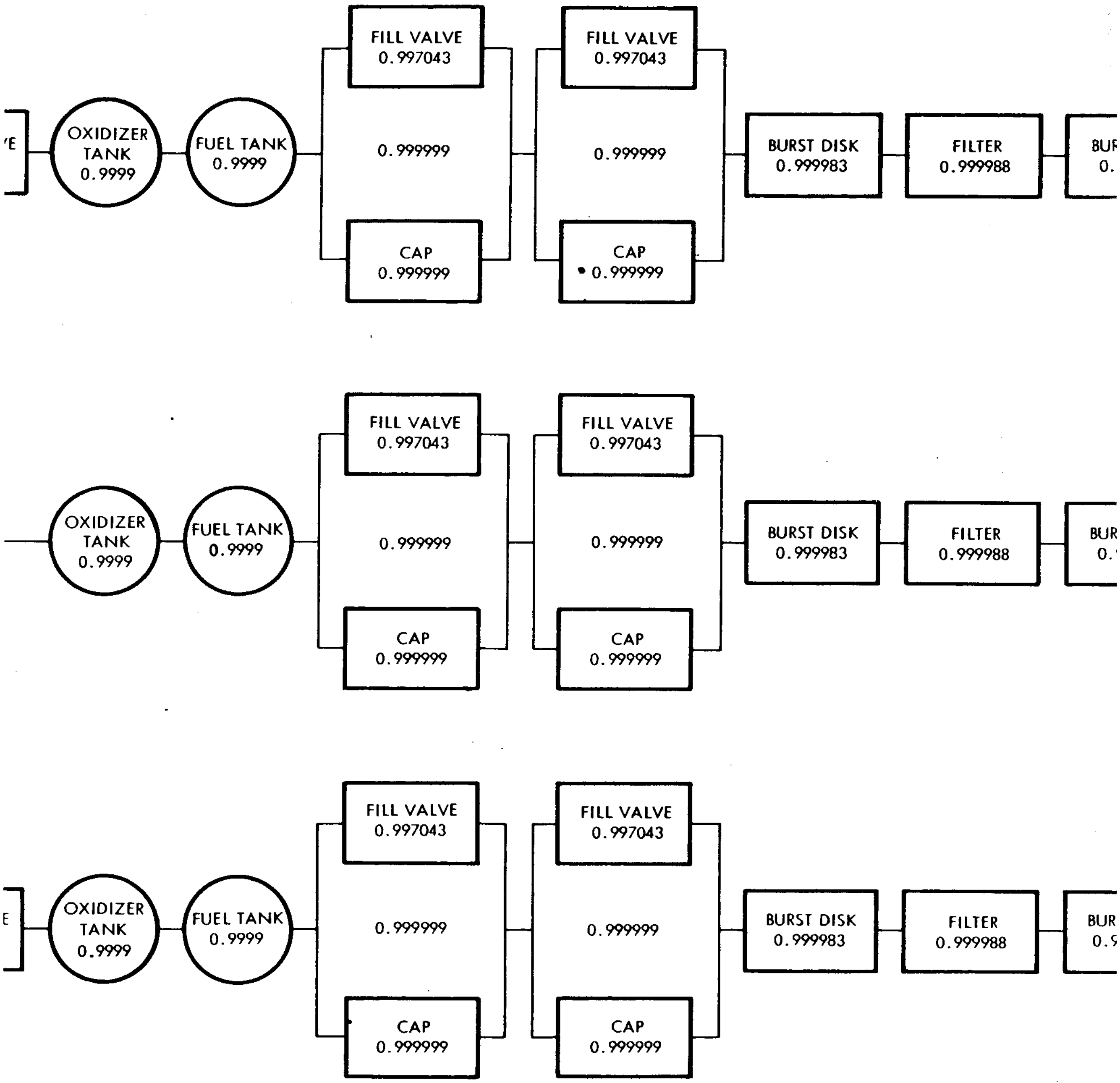


VE
7
9
9
SQUIB VALVE
0.999480
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
PRESSURE
REGULATOR
0.999708
0.999999
PRESSURE
REGULATOR
0.999708
VE
7
9
9
SQUIB VALVE
0.999480
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
RAM

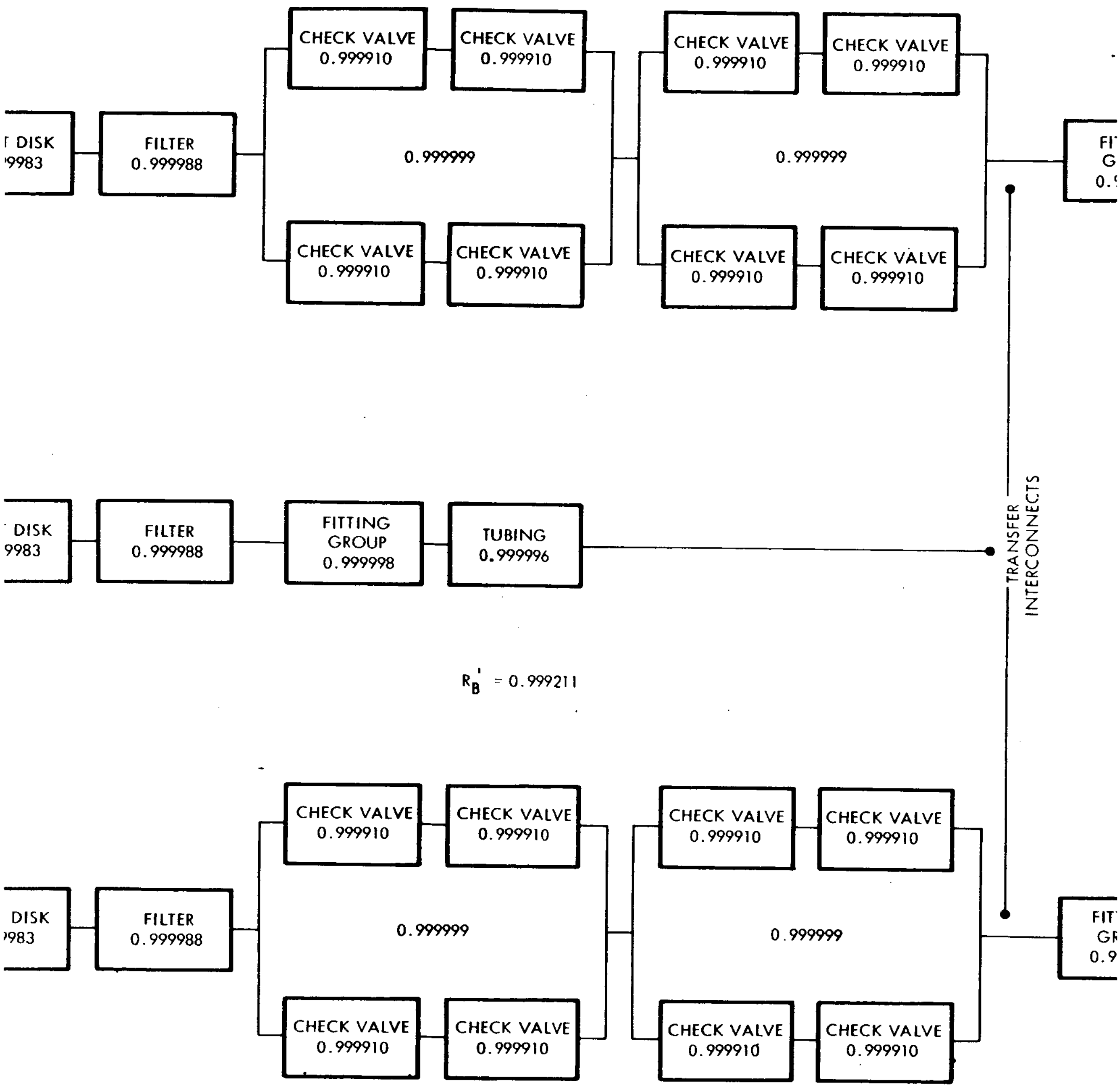
2


B REACTANT SUPPLY
VENT VALVE 0.999850
RELIEF VALVE 0.999850
FILTER 0.999988
0.999999
0.999999
SQUIB VAI 0.99948(
CAP 0.999999
BURST DISK 0.999983
VENT VALVE 0.999850
FITTING GROUP 0.999998
TUBING 0.999998
(STAND-BY OPERATION ONLY)
0.999999
SQUIB VALVE 0.999480
CAP 0.999999
VENT VALVE 0.999850
RELIEF VALVE 0.999850
FILTER 0.999988
0.999999
0.999999
SQUIB VAL' 0.999480
0.999994
CAP 0.999999
BURST DISK 0.999983

3



OXIDIZER TANK 0.9999
FUEL TANK 0.9999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILL VALVE 0.997043
0.999999
CAP 0.999999
BURST DISK 0.999983
FILTER 0.999988
OXIDIZER TANK 0.9999
FUEL TANK 0.9999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILL VALVE 0.997043
0.999999
CAP 0.999999
BURST DISK 0.999983
FILTER 0.999988
OXIDIZER TANK 0.9999
FUEL TANK 0.9999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILL VALVE 0.997043
0.999999
CAP 0.999999
BURST DISK 0.999983
FILTER 0.999988


DISK
9983
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
DISK
9983
FILTER
0.999988
FITTING
GROUP
0.999998
TUBING
0.999996
TRANSFER
INTERCONNECTS
$R_B' = 0.999211$
DISK
983
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910

5

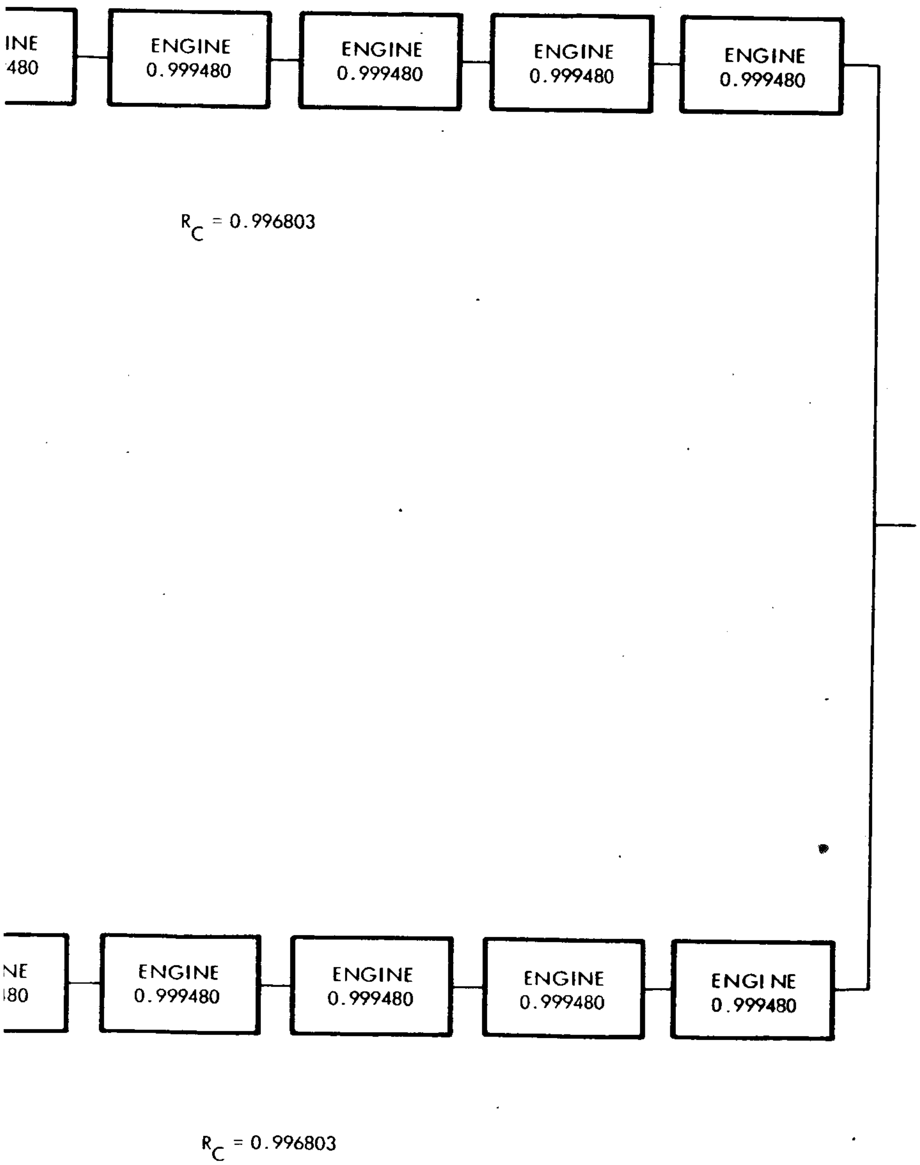
C ENGINE PACKAGE

ING)UP ?998	TUBING 0.999996	FLOW METER 0.999961	FLOW METER 0.999961	FITTING GROUP 0.999999	TUBING 0.999999	ENGINE 0.999480	EN 0.9

$R_B = 0.999208$

NG UP 998	TUBING 0.999996	FLOW METER 0.999961	FLOW METER 0.999961	FITTING GROUP 0.999999	TUBING 0.999999	ENGINE 0.999480	EN(0.9

$_B = 0.999208$



MATHEMATICAL MODEL FC

RELIABILITY = $R_A(R_B{}^2R_C{}^2$ +

\+ $2q_Bq_CR_BR_C$

IN WHICH

R_A = 0.9999

q_A = 0.0000

R_{SV} = 0.999

$R_{(T-3)}$ = (0.999994) [(0.99

+2(0.000792)(0.99

(0.999208)(0.9992

(0.999211)(0.9968

DEFINITIONS:

R_A = RELIABILITY

R_B = RELIABILITY

R'_B = RELIABILITY

R_C = RELIABILITY

R_{VO} = RELIABILITY

R_{SV} = RELIABILITY

q_A = PROBABILIT

q_B = PROBABILIT

q_C = PROBABILIT

Figure 26. Comma
Logic N

COMMAND MODULE REACTION SYSTEM, TRIPLE -3

$q_C R_B R_C R_B' R_{SV} R_{VO}^2 + 2q_B R_B R_B' R_{VO} R_C^2 R_{SV}^2$

$. R_{VO}^2 R_{SV}^2 + 2q_C q_B R_B R_B' R_C R_{VO}^3 R_{SV}^2)$

$R_B = 0.999208,\ R_B' = 0.999211,\ R_C = 0.996803,$

$q_B = 0.000792,\ q_C = 0.003197,$

, and $R_{VO} = 0.999522$

$08)^2(0.999208)^2 + 2(0.003197)(0.999208)(0.996803)(0.999211)(0.999761)(0.999522)^2$

$)8)(0.999211)(0.999522)(0.996803)^2(0.999761)^2 + 2(0.000792)(0.003197)$

$(0.999522)^2(0.999761)^2 + 2(0.003197)(0.000792)(0.999208)$

$(0.999522)^3(0.999761)^2 \Big| = 0.999973$

)F HELIUM PRESSURIZATION SUBSYSTEM
)F PROPELLANT SUBSYSTEM
)F REDUNDANT PROPELLANT SUBSYSTEM
)F ENGINE SUBSYSTEM
)F SOLENOID VALVE OPERATION - 2 VALVES
)F SOLENOID VALVE OPERATION ONLY
OF SUBSYSTEM A FAILING
OF SUBSYSTEM B FAILING
OF SUBSYSTEM C FAILING

l Module Triple 3 Reaction Control System
:twork and Mathematical Model

8

[redacted]

[redacted]

LAUNCH ESCAPE

LAUNCH ESCAPE MOTOR AND PITCH CONTROL MOTOR

Primary emphasis was placed on redefining the launch escape subsystem reliability requirements as a result of replacing the thrust vector control (TVC) design with a pitch control motor. This redirection pertained only to the launch escape motor in conjunction with the pitch control motor, having no effect on the tower jettison motor program.

Reliability Apportionment

The total failure rate of two failures per 1000 motors was reapportioned because of the elimination of thrust vector control. The statistical allocations are shown in Table 17.

Table 17. Launch Escape Motor Reliability Apportionment[1]

Components	Relative Complexity	Complexity Index	Failure Rate	Apportioned Reliability
Nozzle	0.750	0.300	0.0006	0.9994
Igniter and propellant	1.000	0.400	0.0008	0.9992
Case, insulation, and liner	0.750	0.300	0.0006	0.9994
System	2.500	1.000	0.0020	0.9980

The batch process characteristics of solid motors, as well as the fundamental similarity of each component, brings forth by deduction an identical apportionment for the pitch control motor.

[1] Less than one failure per thousand is permitted for each of the subsystems. From a practical viewpoint, each subsystem must have "absolute" reliability because of the essentially catastrophic mode of failure. Further allocation within each subsystem has no significance.

~~CONFIDENTIAL~~

[redacted]

Statistical Approach

Study of statistical methods for demonstrating the reliability of the launch escape motor and the pitch control motor was continued. The approach to reliability for solid fuel rocket motors involves the study of product variability and the selection of adequate safety margins.

If x = case strength (in equivalent pressure units)

y = chamber pressure

m = mean value

σ = standard deviation

then

$$(x_m \pm \sigma_x) - (y_m \pm \sigma_y) = (x_m - y_m) \pm \left(\sigma_x^2 + \sigma_y^2\right)^{\frac{1}{2}} \tag{1}$$

Considering only the positive statistical error for the chamber pressure and the negative statistical error for the case strength, Equation 1 becomes

$$(x_m - \sigma_x) - (y_m + \sigma_y) = (x_m - y_m) \pm \left(\sigma_x^2 + \sigma_y^2\right)^{\frac{1}{2}} \tag{2}$$

In order for the motor to have a high reliability, $x_m - y_m > \left(\sigma_x^2 + \sigma_y^2\right)^{\frac{1}{2}}$ must be the case all of the time, because a failure would occur when

$$x_m - y_m \leqq \left(\sigma_x^2 + \sigma_y^2\right)^{\frac{1}{2}}$$

Thus, it is clear that:

Reliability increases as the standard deviations decrease.

Reliability increases if

$$x_m - y_m > \left(N\sigma_x^2 + N\sigma_y^2\right)^{\frac{1}{2}}$$

when

$$N = 1,\ 2,\ 3 \ldots\ n$$

[redacted]

[redacted]

Figures 27 and 28 show the above relationships. It is noted that the proof pressure was increased from 2700 psi to 3000 psi for the pitch control motor. If the following expression is considered the lower boundary for the demonstration of reliability,

$$(x_{p_m} - y_m) = \left(3\sigma_x^2 + 3\sigma_y^2\right)^{\frac{1}{2}}$$

in which x_{p_m} equals mean proof pressure when proof is considered as a certain fixed percentage of yield pressure

then the number of standard deviations can increase, as the proof pressure increases, to maintain the equality which, in turn, increases the reliability.

TOWER JETTISON MOTOR

Results of hydrostatic tests indicate excellent margins of safety in the motor and pyrogen hardware. The motor case and closure assembly withstood 2950 psi without failure; the pyrogen case burst at 7900 psi. These are 100-percent and 300-percent safety margins over nominal operating pressures.

Reliability Apportionment

The reliability requirement of 0.99995 for the rocket motor has been reapportioned in more detail. Since the numbers become excessively high and impossible to demonstrate, no further effort will be spent on apportioning the reliability. The detailed reapportionment is presented in Table 18.

Failure-Mode Analysis

A detailed study was made of the possible modes of failure and the effects of the failure on the Apollo tower jettison motor. The failure-mode analysis will be used as an input for the reliability-stress analysis. The results of the failure-mode analysis are presented in Table 19.

Reliability Prediction

Based on usage of the major parts of the tower jettison motor in similar applications, but of different sizes and configurations, it is estimated that the motor has theoretically demonstrated a reliability of 0.97 at the 95-percent confidence level. This is equivalent to 100 tests without failure.

~~CONFIDENTIAL~~

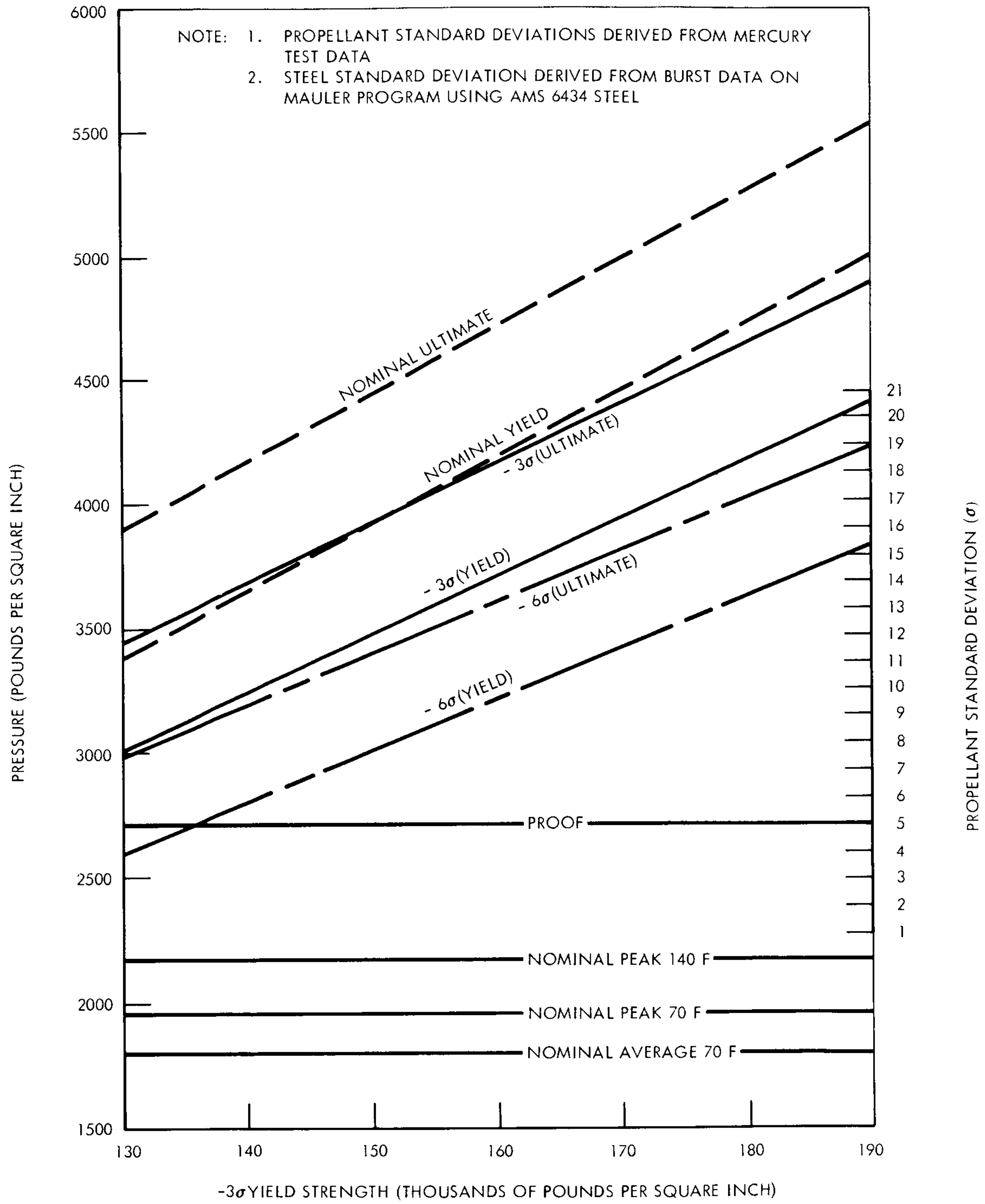


Figure 27. Parametric Study of the Apollo Pitch Control Motor

~~CONFID~~[redacted]

[redacted]

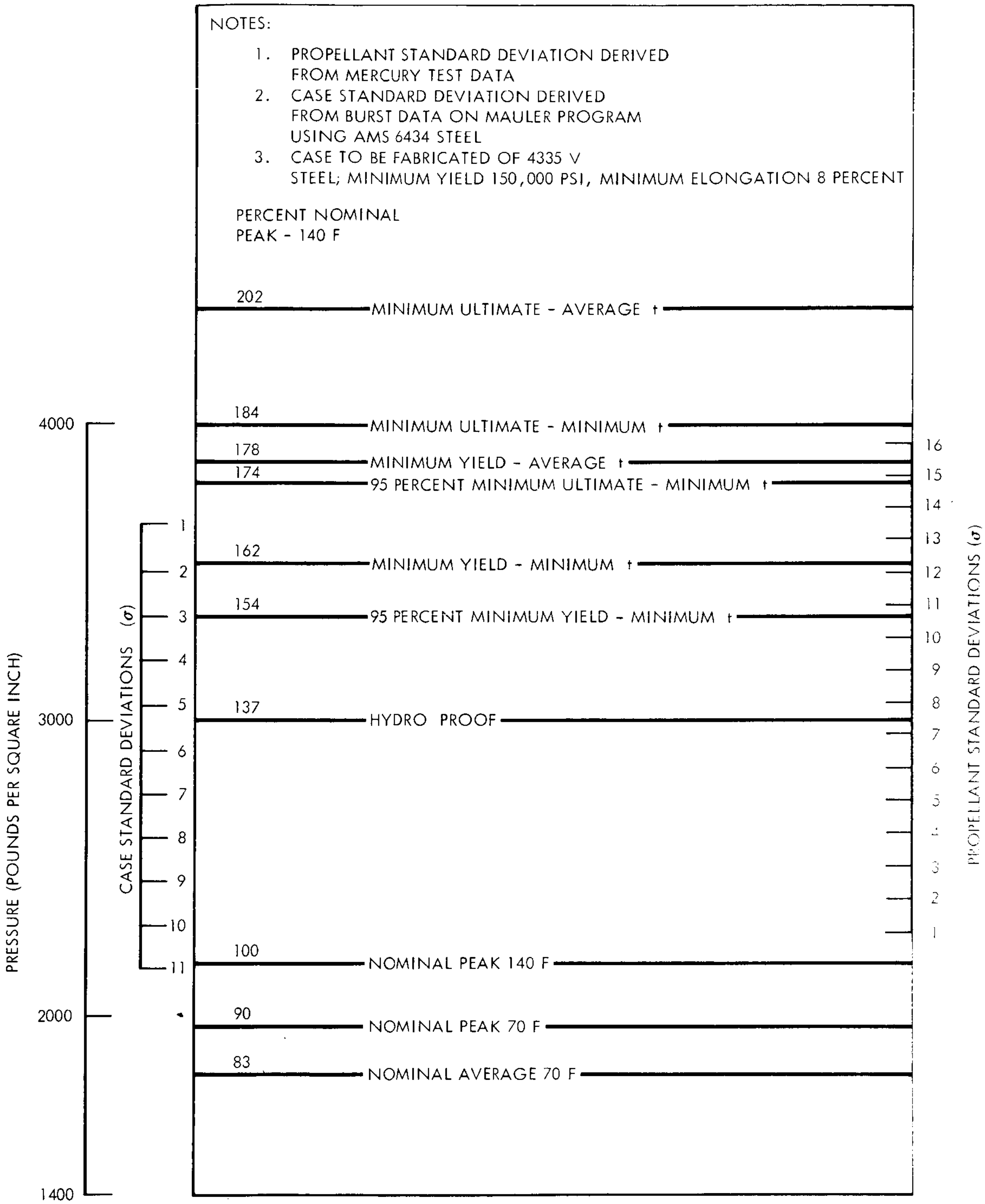


Figure 28. Design Criteria for the Apollo Pitch Control Motor

[redacted]

Table 18. Tower Jettison Rocket Motor Reliability Apportionment

Subsystem	Reliability	Major Components	Reliability
Ignition	0.9999960	Initiators (EBW) Pyrogen case Pyrogen propellant	0.9999990 0.9999980 0.9999990
Propellant	0.9999990	Propellant material Propellant grain	0.9999998 0.9999992
Pressure vessel	0.9999980	Case Aft closure Pressure seal Liner Insulation	0.9999999 0.9999995 0.9999994 0.9999998 0.9999994
Nozzle system	0.9999570	Housing and expansion cone Nozzle insert Nozzle closure Closure seal External insulation	0.9999990 0.9999700 0.9999980 0.9999906 0.9999994
Rocket motor assembly	0.9999500		0.9999500

Table 20 is a summary of the history of components similar to the tower jettison motor components. Data from other rocket motor programs were used only if the motor met the following criteria:

Web burn-time = minimum 1.5 seconds

Flame temperature = minimum 4188 F

Propellant aluminum content = minimum 2 percent

Characteristic velocity = minimum 4465 feet per second

The only deviation in material selection was for the carbon insert, where HLM, ATJ, and AGX carbon were grouped together.

Calculation of system reliability was based on confidence limits for the binomial distribution. Component reliability was estimated by the product rule, assuming six components. For example, it was reasoned that in order for six independent components to combine for a reliability of 0.987, then each component had to have a reliability of 0.9978.

[redacted]

Table 19. Tower Jettison Rocket Motor Failure-Mode Analysis

Component	Failure Mode	Effect on System
Igniter assembly		
Initiator (EBW)	No fire Excessive brisance	Dud Rupture of boron pellet container E13814B releasing pellets and reducing pyrogen pressure
Igniter assembly (pyrogen)	Pressure leakage initiator "O" ring MS9020-06	Possible loss in motor pressure
Pyrogen case	Burst or rupture	If prior to motor ignition, dud. After motor ignition, loss of motor pressure
Pyrogen propellant	Cracked grain	High ignition pressure (burst pyrogen case)
	Voids	Slight change in pressure
Motor propellant grain (TP-E-8104)	Crack grain	Increased surface area, pressure, and thrust if in star points or web Increase heating of case if in web (surface to case) Rupture of case assembly
	Voids	Increase surface area, pressure, and thrust if close to surface No effect if close to case wall
	Low burn rate	Increased in burn time; reduced pressure, and thrust
	High burn rate	Reduced burn time; increased pressure and thrust
	Propellant-to-case separation	Initially - increased surface area, pressure, and thrust if at nozzle end No effect if random spots internal to exposed surface after environments Poor resistance to shock, temperation cycle, and vibration, if present at assembly Cracked propellant

[redacted]

~~CONFIDENTIAL~~

Table 19. Tower Jettison Rocket Motor Failure-Mode Analysis (Cont)

Component	Failure Mode	Effect on System
Case and closure sub-assembly		
Motor case	Rupture	Cracked propellant Loss of pressure
	Yielding	Pressure leakage Cracked insulation Propellant-to-case separation Cracked propellant
Seals (Buna-N "O" ring)	Pressure leakage	Reduced thrust Hot spot and erosion at leakage point
Insulation* (Gen. Gard V-44)	Cracked insulation	Hot gas impingement on bulkhead
Liner (TED-100L)	Missing liner	Propellant-to-case separation
Nozzle assembly		
Nozzle insert	Cracked	Loss of insert; loss of pressure and thrust
	Voids	Excessive erosion Induced structural loads
	Excessive erosion	Reduction in pressure and thrust Reduction in structural strength
Nozzle closure	Missing	Loss of ignition in vacuum Contamination of propellant Longer delay time at sea level
Expansion cone	Excessive erosion	Increase in $\frac{Ae}{At}$ (increase in thrust).
	Excessive build-up	Decrease $\frac{Ae}{At}$ (decrease in thrust).
Seals, "O" ring closure	Pressure leakage	No effect
Structure	Yielding	Loss of nozzle insert Loss of nozzle insulation Pressure leakage from motor

*Heat transfer analysis indicates that case burn-through probably would not occur even if the insulation were missing.

~~CONFIDENTIAL~~

[redacted]

Table 20. Reliability History of Components

Component	System Tested	Test Failed	System Reliability at 95-Percent Confidence	Component Reliability*
Propellant (TP-E-8104)	231	0	0.987	0.9978
Insulation (V-44)	24	0	0.883	0.9795
Igniter (TP-E-8104)	231	0	0.987	0.9978
Nozzle insert (HLM Carbon)	1350	0	0.9975	0.9996
Nozzle cone (4130 Steel)	571	1	0.9915	0.9986
Liner (TED-100L)	202	0	0.985	0.9975

*$R_T = 0.9978 \times 0.9795 \times 0.9978 \times 0.9996 \times 0.9986 \times 0.9975$

$R_T = 0.9710$

It is planned to predict reliability at the completion of developmental testing based on the reliability-stress and failure-mode analyses. If sufficient data are available, the probability that the failures listed in Table 16 would not occur will be used for prediction.

[redacted]

HIGH ALTITUDE ABORT

RELIABILITY STUDY

A reliability study to compare six proposed configurations for initiating a high altitude abort was completed. Results of the study show configuration 6b, which contains four posigrade rocket motors mounted on the service module exterior, to be the most reliable configuration. Based on a low probability of failure, absence of need for an extensive design development program, and the inherent reliability of solid-propellant rocket motors, this configuration was recommended.

FAILURE-MODE ANALYSES

Table 21 is a failure-mode analysis and contains the system probability of failure for the six configurations evaluated.

Table 22 is a failure-mode analysis for configurations 5 and 6, using the requirement that a 60-inch separation of the command module-service module unit from the S-IVB booster vehicle must occur in two seconds. Probabilities of failure are given for the two configurations, considering earth orbit missions using the C-1 and C-1B booster configurations, and using the C-5 booster configurations for the lunar mission. For all missions, abort rocket configuration 6b was the most desirable from the reliability viewpoint.

ABORT SYSTEM CONFIGURATIONS

The configurations evaluated are as follows:

Configuration 1

Four blow-out panels are located in the service module adapter. To effect separation of the command-module, service-module unit from the S-IV stage adapter, the service module propulsion system is fired after firing strip charges to remove the blow-out panels.

Misfire of the strip charges and failure to remove the blowout panels would present the hazard of critical damage to the service module propulsion system nozzle (partial nozzle burn-through and consequent side-thrust vector). Location of the blowout panels in the service module adapter in the area above the nozzle outlet raises a question as to their effectiveness.

Table 21. High Altitude Abort System Failure-Mode Analysis

Proposed Configuration	Failure Mode	Effect on Crew Survival	Failures Per Million Missions	Corrective Action
1	Does not blow out panels Valve failure	Critical	230	Redundancy; retrorockets and reaction control system available
2	Does not blow out panels Valve failure	Critical	230	
3	Does not blow out panels Valve failure	Critical	1280	
4	Insufficient clearance RCS failure	Critical	4000	Redundancy with service module system available
5	Insufficient clearance RCS failure Retrorocket failure	Critical	50	Redundancy with service module propulsion system Not a self-contained capability
6	Single-engine failure Multiple-engine failure	Minor Critical	110	Redundancy with reaction control system, service module propulsion system, and retro-rockets

[redacted]

Table 22. Normal Separation and High-Altitude Abort, Configurations 5 and 6b Failure-Mode Analysis

Mission	Configuration	Failure Mode	Effect on Crew Survival	Failures Per Million Missions	Corrective Action
C-1	6 b Four posigrade rockets, exterior mounted	Engine failure Insufficient clearance	Critical	72	Redundancy with RCS and SPS (Redundancy exists with reaction control system and service module propulsion system).
	5 - Two retrograde rockets	Engine failure Insufficient clearance	Critical	990	Redundancy with RCS and SPS Not a self-contained capability.
C-1B	6 b Four posigrade rockets, exterior mounted	Engine failure Insufficient clearance	Critical	72	Redundancy; RCS, SPS.
	5 - Four retrograde rockets	Engine failure Insufficient clearance	Critical	1010	Redundancy; RCS, SPS. Not a self-contained capability.
C-5	6 b Four posigrade rockets, exterior mounted	Engine failure Insufficient clearance	Critical	72	Redundancy; RCS, SPS.
	5 - Eight retrograde rockets	Engine failure Insufficient clearance	Critical	1030	Redundancy; RCS, SPS. Not a self-contained capability

RCS = reaction control system

SPS = service module propulsion system

[redacted]

Configuration 2

This configuration is similar to configuration 1, but it includes the addition of an internal diverter attached to the S-IV stage adapter, with the tip of the diverter extending into the opening of the service module propulsion system nozzle.

Failure modes of configuration 2 are the same as those of configuration 1.

Configuration 3

Configuration 3 is similar to configuration 2; however, the blowout panels (a total of four) are located in the S-IV stage adapter. Also, the internal diverter is extended into the S-IV stage adapter.

Failure modes of configuration 3 are the same as those of configurations 1 and 2. Possible redundancy of the two retro rockets in the S-IV stage and the reaction control system of the service module are not considered in reliability calculations of configurations 1, 2, or 3.

Configuration 4

This configuration proposes utilization of the reaction control system to effect separation (60 inches required) of the command-module, service-module unit from the S-IV stage adapter prior to firing the service module propulsion system.

If allowable time for separation were short, the limited thrust of the reaction control system (400 pounds total) could be responsible for failure to successfully abort. If an ullage problem existed, malfunction of the positive expulsion diaphragms and associated solenoid valves in the reaction control system fuel supply system could cause misfire of the reaction control system and failure of the abort.

The retro rockets and the service module propulsion system offer possible redundant support to configuration 4.

Configuration 5

Configuration 5 proposes utilization of two retro rockets (in the S-IV stage) acting simultaneously with the reaction control system to effect a 60-inch separation of the command-module, service-module unit from the S-IV stage adapter prior to firing the service module propulsion system.

If allowable time for separation were short, the limited thrust (7000 pounds total) of the retro rockets acting on the mass of the S-IV stage, and the reaction control system (400 pounds total) acting on the command-module, service-module unit might be incapable of effecting separation soon enough to avoid failing an abort. Reliance on the retro rockets poses a hazard, since the retro rockets could conceiveably contribute to the need to abort. Further, the capability to abort would not be entirely self-contained. An added hazard in this system arises from possible malfunction of the reaction control system. The service module propulsion system does offer possible redundant support to configuration 5.

Configuration 6

This configuration proposes the utilization of four posigrade rocket motors (21,500 pounds total thrust) attached to the service module (interior mounted, configuration 6a; exterior mounted, configuration 6b) to effect separation of the command-module, service-module unit from the S-IV adapter in one second, prior to firing the service module propulsion system.

Failure of one posigrade rocket would result in a small change of direction of the spacecraft unit separating from the S-IV stage adapter, but this probably would not be critically important. Multiple posigrade rocket failure could have a critical effect on an attempted abort. The service module propulsion system, the reaction control system, and the S-IV retro-rockets provide possible redundant support for configuration 6.

ELECTRICAL POWER

FUEL CELL SUBSYSTEM

A revised numerical reliability analysis was performed on the fuel cell system. The following changes were made to the system as a result of redesign of the fuel cell.

Flow meters and appropriate instrumentation were removed.

Squib valves were removed.

The system was changed to a conical mount configuration, including the addition of flexible lines.

The revised analysis provided a basis for apportionment of the system crew-safety requirement of 0.99999 to establish revised individual fuel cell module and component reliability requirements. The reliability apportionment for the module is 0.9785. On this basis, the normal power reliability requirement for a three-module system is 0.9986.

RELIABILITY FUNCTIONS

The fuel cell system is an arrangement of three independent modules. For purposes of computing crew-safety reliability, two out of the three modules are assumed to fail. The reliability function is

$$R_{safety} = 1 - (1 - R_m)^3$$

in which

$$R_m = \text{independent module-reliability requirement.}$$

When

$$R_{safety} = 0.99999$$

$$R_m = 1 - \sqrt[3]{1 - R_{safety}}$$

$$= 1 - \sqrt[3]{0.00001}$$

$$= 0.9785$$

For purposes of computing normal-power reliability, only one of the three modules is assumed to fail. The reliability function is

$$R_{\text{normal power}} = R_m^3 + 3R_m^2 (1 - R_m)$$

$$= 3R_m^2 - 2R_m^3$$

$$= 0.9986$$

FAILURE-RATE RERANKING

Failure rates were reranked on the basis of a study of the following:

The recently completed first design

Some early testing results

Some recently published failure information

This study resulted in assigning failure rates to the fuel cell components that differ from those assigned during the preliminary design.

As a result of the system changes already discussed and the anticipated reliability growth through Phase A of the development program, predicted independent-module reliability is 0.898. This estimate will be periodically updated.

COMPONENT RELIABILITY REQUIREMENTS

The independent module reliability requirement of 0.9785, which incorporates a 400-hour mission time and the present relative failure rates assigned to all components, was apportioned to establish component reliability requirements as shown in Table 23.

MONTE CARLO ANALYSIS

A Monte Carlo program was completed for the fuel cell and is now being run. This program reflects the latest changes in the bill of materials and the changes in the reliability apportionment described above.

[redacted]

Table 23. Electrical Power System Component Reliability Requirements

Component	Number of Components in System (n)	Failure Rate (λ)(x 10^6)	Operating Time (t) (hours)	nλ tx10^6	Reliability
Cell stack	1	52.75	400	21,100.0	0.9791
Motor-pump/separator - valve assembly	1	0.46	400	184.0	0.99982
Motor-pump assembly (glycol)	1	0.16	400	64.0	0.999936
Nitrogen regulator	1	0.26	400	104.0	0.99990
Oxygen regulator	1	0.22	400	88.0	0.999912
Hydrogen regulator	1	0.22	400	88.0	0.999912
Regenerator bypass, hydrogen	1	0.16	400	64.0	0.999936
Accumulator	1	0.045	400	18.0	0.999982
Regenerator bypass, glycol	1	0.080	400	32.0	0.999968
Heat exchanger	1	0.0060	400	2.4	0.9999976
Manifolds and tubing and mechanical connections	1	0.0040	400	1.6	0.9999984
Tank	1	0.0020	400	0.8	0.99999920
Support and housing	1	0.0020	400	0.8	0.99999920
Heater and wiring	1	0.0003	400	0.12	0.99999988
Instrumentation	1	**	400	0.0064	0.9999999936
Purge valve	2	0.40	1	0.80	0.99999920
Relief valve	1	0.24	1	0.24	0.99999976
Fill valve	1	0.00014	1	0.00014	0.99999999986
Total, independent module				21,748.76654	0.9785

λ = Failure rate
**Redundancy involved

[redacted]

DESIGN REVIEWS

Since a major portion of the past quarter's design reviews involved revisions to previously reviewed layouts, few improvements were suggested. Designs for which significant increases in reliability were effected are as follows.

Fuel Cell Tubing

The OD and wall thickness of all tubing on the fuel cell element were increased, and welding techniques for fill tubes were improved.

Hydrogen Pump and Separator

The water discharge valve was redesigned to provide for external testing of bellows and valve operation. Construction was improved by machining the valve from one piece instead of two; also, a screen was added on the inlet porting to prevent foreign particles from entering the valve.

Pump Manifold and Condenser

Mounting brackets were improved to prevent overstressing of bolted connections.

Glycol Accumulator

Tank joint and boss connections were changed to an all-braced design; this improves manufacturing by allowing joints to be brazed at the same time, and it simplifies the anodizing of internal surfaces.

Bypass Control Support

This support was changed to a split teflon bushing with retaining rings to facilitate manufacturing and to prevent any loss of clamping due to vibration.

DEVELOPMENT PROBLEMS

Many of the difficulties encountered in development were a logical result of changing from the sub-scale cells in which a background of experience existed to the full-size cells. The concomitant change in sinter diameter introduced welding problems, evidenced by delamination and blistering on early samples. The change from the familiar, open electrolyte volume to a sealed volume caused temporary mechanical difficulties with fill tubes, and also caused a problem in obtaining proper filling and distribution of the electrolyte. This last problem has not yet been completely resolved, but it is yielding to a concerted effort on the part of design and development engineers.

MATERIALS IMPROVEMENT RESULTING FROM TESTING

During the present phase of development, an area of particular concern is development testing. Reliability engineers monitor the tests and evaluate their results in order to assess the achieved level of reliability and to verify that alternating design improvements and retesting are bringing about the desired growth in reliability. Most testing to date has been on materials; however, the test program recently entered a new phase, testing of complete components. Typical materials and components which are now at a satisfactory reliability level, or in which substantial improvement has been effected, are discussed in the following paragraphs.

Insulation

Salt-spray tests of insulating materials, using a 20-percent salt solution, showed Linde SI-62 Super Insulation to be a satisfactory material.

Tube Connectors

Fatigue tests and pressure tests were performed on tube connectors of both commercial design and a special Apollo design. Figure 29 illustrates typical test results obtained from the Apollo design.

Fuel Cell Diaphragms

A comprehensive program of structural tests is underway to evaluate the resistance of cell diaphragms and sinters to pressure and vibration loading. For ease of testing, mercury was used instead of molten KOH electrolyte (air pressure simulated expansion of the electrolyte). These tests are continuing as design improvements are incorporated.

Seals and Gaskets

Seal and gasket-material samples were tested for corrosion resistance by immersion in beakers of molten KOH, and by exposure to KOH at high temperature and pressure in enclosed pressure chambers, or bombs, as illustrated in Figure 30. Several materials were eliminated from consideration by such tests. Promising materials were further evaluated by a multiple-seal test rig simulating actual conditions in a stack of fuel cells (Figures 31 and 32).

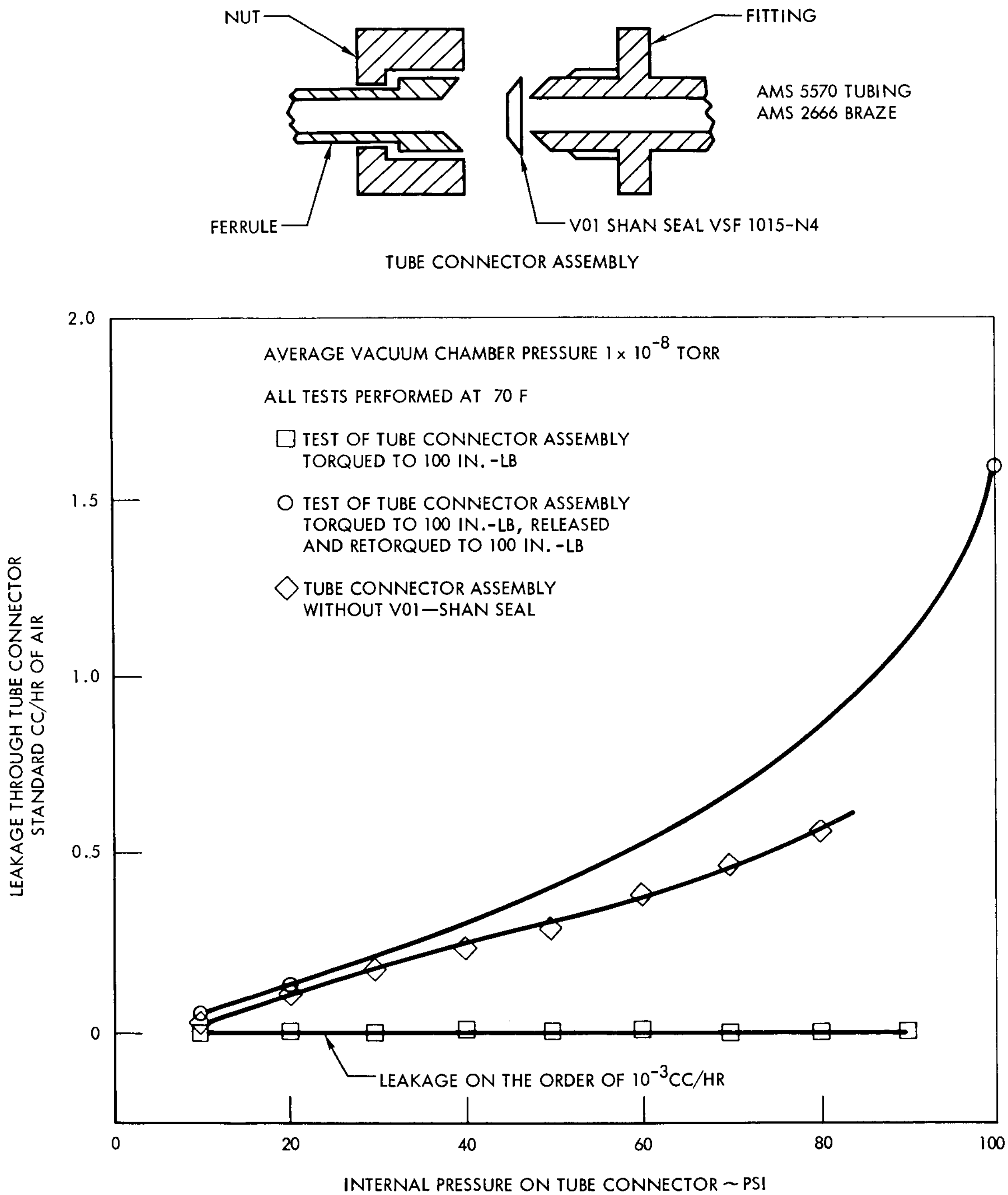


Figure 29. Apollo Tube Connector Leakage

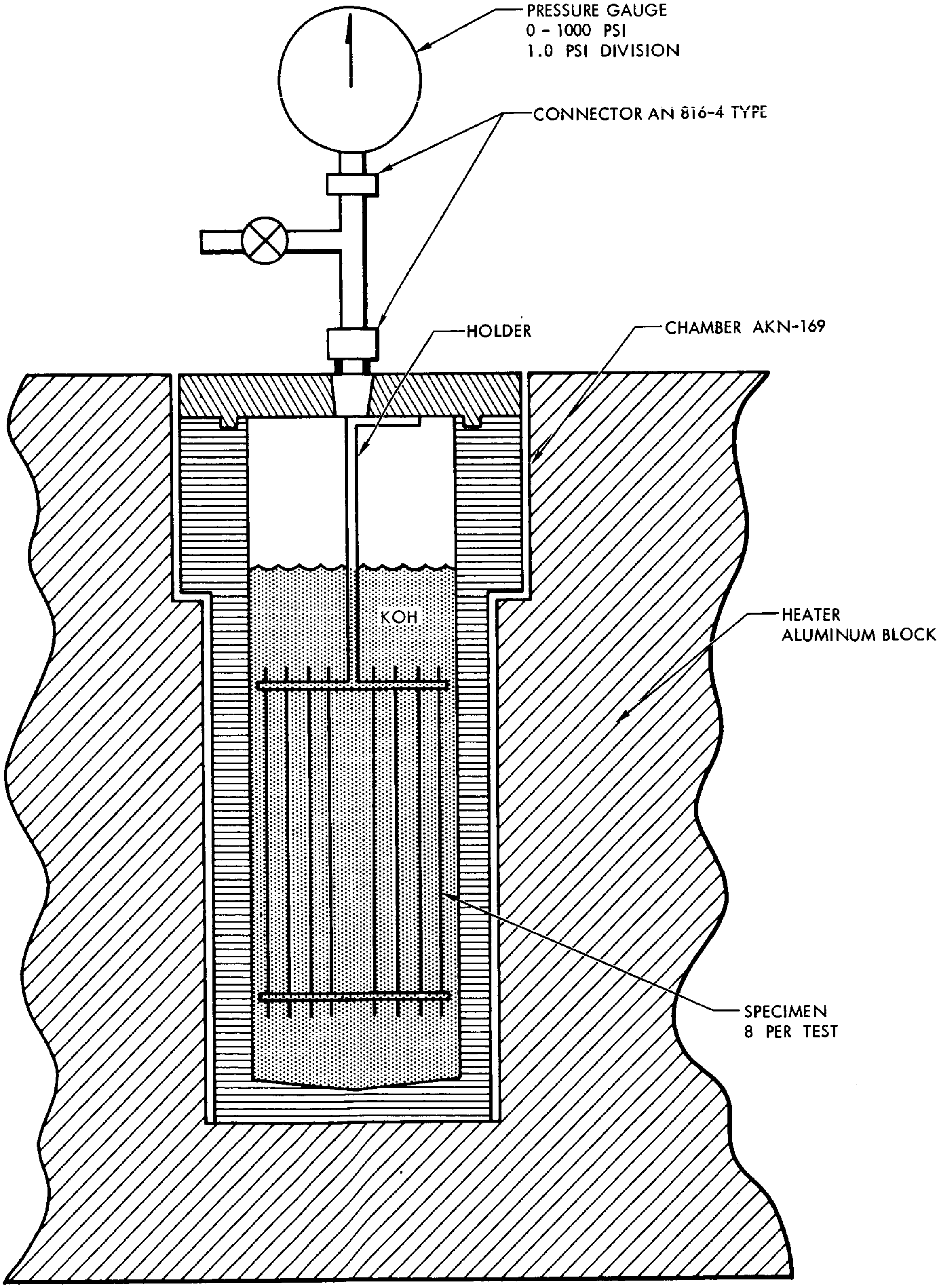


Figure 30. Compatibility Test Rig Assembly

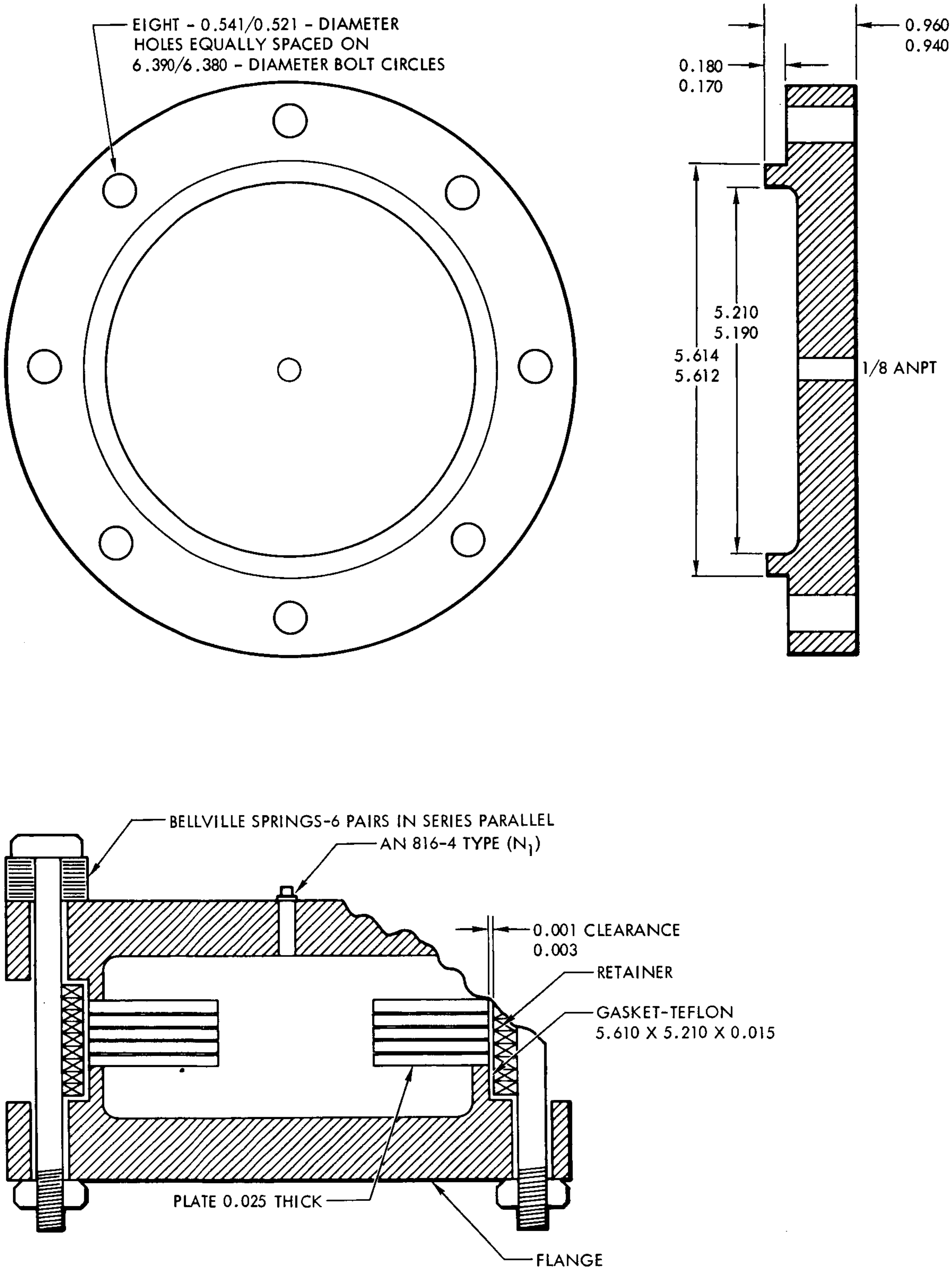


Figure 31. Multiple-Seal Test Rig

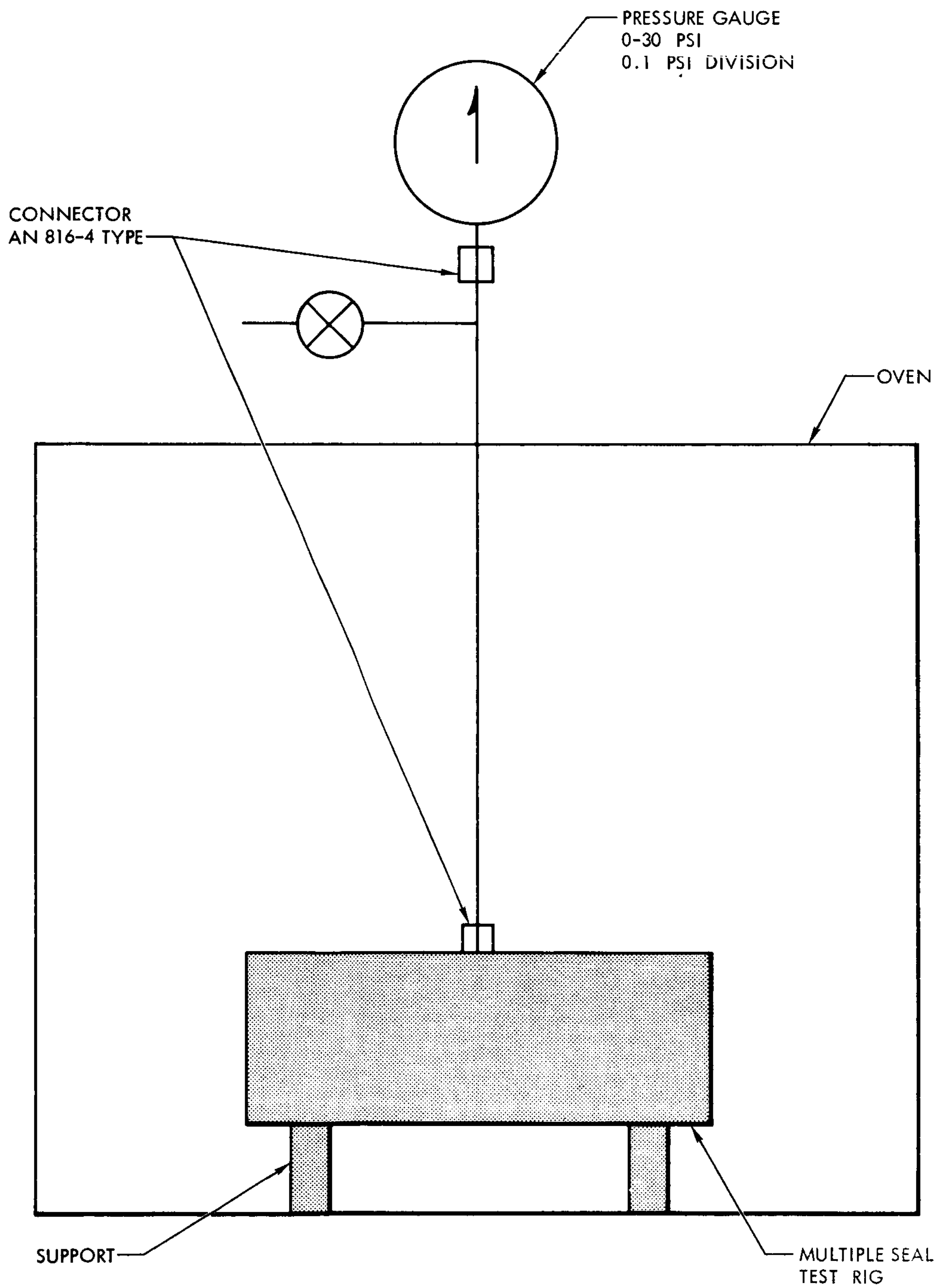


Figure 32. Multiple-Seal Test Assembly

Coolant Pump

The only lubricant available to the gear pump used to circulate the glycol-water mixture is the mixture itself; therefore, a test program leading to selection of suitable gear and journal combinations is essential to guaranteeing reliability of this pump. Various combinations of steel, aluminum, plastic, and carbon were tested; life of pump parts is being extended as the program progresses.

Hydrogen Pump

This positive-displacement pump uses vanes sliding in slots to propel a mixture of hydrogen and water. Since the water must be drinkable, erosion of particles from the vanes and the pump liner must be held to a minimum. Tests with different materials yielded steady improvement in pump life and a reduction in particle production; the final design uses Graphitar vanes and a chrome-plated, stainless steel liner.

Heat Rejection Loop

Reliable operation of the secondary heat-rejection loop requires that the small passages of valves and heat exchangers not become clogged by particles of foreign matter. A group of corrosion loops were operated with various cooling mixtures under different temperature conditions to investigate the possibility of corrosion, precipitate formation, and fluid property changes. Parallel corrosion tests were performed in nickel bombs at various temperatures and pressures. Chemical and metallurgical analyses were performed on fluids and metal parts at the conclusion of the tests. Glycol was found to be superior to Zerex in this application.

DISTRIBUTION SUBSYSTEM

A failure-mode analysis has been conducted for the electrical power distribution subsystems and the static inverters. The failure-mode analysis of the electrical distribution subsystem (Table 24) has two first-order failure modes that could cause loss of the mission and crew. These failure modes are a line failure and a tank rupture in the supercritical gas system. These modes can be precluded by utilizing adequate design margins. The failure-mode analysis for the static inverter is shown in Table 25.

[redacted]

Table 24. Electrical Power Distribution Failure-Mode Analysis

Component	Failure Mode	Probable Cause	Effect on: Available Power	Effect on: Mission Success	Effect on: Crew Safety	Corrective Action
Reactant supply system	Loss of O_2	Line failure Tank rupture	Loss	Loss	Loss	Design margins
	Loss of H_2	Line failure Tank rupture	Loss	Loss	Loss	
Fuel cells	Loss of AC pump power	Feeder line failure Connector failure	1 mod fail: 1/3 2 mod fail: 2/3 3 mod fail: 3/3	1 mod fail: 1/3 2 mod fail: 2/3 3 mod fail: 3/3	1 mod fail: 1/3 2 mod fail: 2/3 3 mod fail: 3/3	
	Zero output	Reactant supply failure Internal component failure	Same	Same	Same	
	Overheating	Glycol pump fails Radiator failure Regenerator by-pass valve fails	Same	Same	Same	Pilot would shut down module if overheating occurred.
Remote control circuit breakers (6)	Inadvertent open	Shock Vibration Current surge	None	None	None	Redundancy used to preclude catastrophic failure
	Fails to open	Contact weld	-1/3 power	None	None	Would cause removal of fuel cell from line.
DC Bus (2)	Short	Vibration Shock	None	None	None	Redundancy used to preclude catastrophic failure
Battery charger (2)	Loss of output	Internal failure Vibration Shock	None	None	None	Redundancy used to preclude catastrophic failure
Battery charger output relay (2)	Fails to open	Contact weld	None	None	None	Redesign of charger circuit. (Failure to close would result in loss of recharge capabilities.)
	Fails to close	Fatigue Shock Vibration	-1/2 Battery Power	None	None	

[redacted]

~~CONFIDENTIAL~~

Table 24. Electrical Power Distribution Failure-Mode Analysis (Cont)

Component	Failure Mode	Probable Cause	Effect on Available Power	Effect on Mission Success	Effect on Crew Safety	Corrective Action
Batteries, A and B	Low voltage No output	Vibration Shock Corrosion	-1/2 Battery Power	None	None	Redundancy used to preclude catastrophic failure
Battery output circuit breaker (4)	Inadvertent opening	Shock Vibration Current surge	None	None	None	Redundancy
	Fails to open	Contact weld	None	None	None	
Battery normally closed output relay (4)	Fails to open	Contact weld	None	None	None	Redundancy
	Fails to close	Fatigue Vibration	None	None	None	
Inverter input relays (6)	Fails to open	Contact weld	None	None	None	Redundancy
	Fails to close	Fatigue Shock Vibration	None	None	None	
Inverter supply circuit breakers (6)	Fails to open	Contact weld	None	None	None	Redundancy used to preclude catastrophic failure
	Inadvertent open	Vibration Shock Current surge	None	None	None	
DC bus feed diodes (6)	Shorts	Heating	None	None	None	Redundancy
	Open	Heating Excessive current	None	None	None	
DC load circuit breaker (2)	Fails to open	Contact weld	None	None	None	Redundancy
	Inadvertent open	Vibration Shock Current surge	None	None	None	
DC load blocking diode	Shorts	Heating	None	None	None	Redundancy
	Open	Heating Excessive current				

[redacted]

Table 24. Electrical Power Distribution Failure-Mode Analysis (Cont)

Component	Failure Mode	Probable Cause	Effect on Available Power	Effect on Mission Success	Effect on Crew Safety	Corrective Action
Battery charger circuit breaker (2)	Fails to open	Contact weld	None	None	None	Redundancy
	Inadvertent open	Vibration Shock Current surge	None	None	None	
Battery charger DC supply	Shorts	Heating	None	None	None	Redundancy
	Opens	Heating Excessive current	None	None	None	
Inverter input blocking diodes (6)	Open	Heating Excessive current	None	None	None	Redundancy used to preclude catastropic failure
	Short	Heating	None	None	None	
Inverters	Output out of required limits		1 inv fail: none 2 inv fail: none 3 inv fail: loss	1 inv fail: none 2 inv fail: loss 3 inv fail: loss	1 inv fail: none 2 inv fail: none 3 inv fail: loss	Redundancy
Inverter output relays (6)	Fail to open	Contact weld	None	None	None	Redundancy
	Fail to close	Vibration Fatigue Shock	None	None	None	
Inverter output circuit breakers (6)	Fail to open	Contact weld	None	None	None	Redundancy
	Inadvertent open	Shock Vibration Current surge	None	None	None	
AC bus (2)	Short	Vibration Shock	None	None	None	Redundancy
AC load circuit breakers	Fail to open	Contact weld	None	None	None	Redundancy
	Inadvertent open	Vibration Shock Current surge	None	None	None	

[redacted]

Table 25. Static Inverter Failure-Mode Analysis

Section and function	Malfunction *	Effect on Single Inverter	Output: Unusable	Output: Limited Usability	Effect on: Mission Success	Effect on: Crew Safety	Corrective Action
DC line filter	1	Out of spec		Yes **	1 inv fail: none 2 inv fail: loss 3 inv fail: loss	1 inv fail: none 2 inv fail: none 3 inv fail: loss	A three inverter stand-by system will be used, thus preventing the loss of power due to a single inverter failure. Circuit analysis during development will determine feasibility of utilizing redundancy for critical items. A component improvement program should be initiated to improve the reliability since the failure of any component is detrimental to the inverter.
	2	Loss of inverter	X				
	3	Loss of inverter	X				
	4	Out of spec		Yes **			
Voltage booster	1	Loss of inverter	X		Same	Same	
	2	Loss of inverter	X				
	3	Loss of inverter	X				
	4	Loss of inverter	X				
DC boost filter	1	Out of spec		Yes Δ	Same	Same	
	2	Loss of inverter	X				
	3	Loss of inverter	X				
	4	Out of spec		Yes Δ			
Power inversion	1	Out of spec		Possible Δ	Same	Same	
	2	Loss of inverter	X				
	3	Loss of inverter	X				
	4	Out of spec		Possible Δ			
Harmonic neutralization interconnection	1	Out of spec	X		Same	Same	
	2	Loss of inverter	X				
Output AC filter	1	Loss of inverter	X		Same	Same	
	2	Loss of inverter	X				
	3	Loss of inverter	X				
	4	Loss of inverter	X				
Current-sensing transformers	1 2 3 4	Out of spec or Loss of inverter, dependent on failure location	Unusable or limited, dependent on failure location Δ		Same	Same	

Δ Dependent on nature of load as to harmonic sensitivity and wave distortion.

* Nature of malfunction

1 Series element short
2 Series element open
3 Shunt element short
4 Shunt element open

** Dependent on tolerance level of DC line to current spiking.

[redacted]

Table 25. Static Inverter Failure-Mode Analysis (Cont)

Section and function	Malfunction*	Effect on Single Inverter	Output: Unusable	Output: Limited Usability	Effect on: Mission Success	Effect on: Crew Safety	Corrective Action
Zener diode reference bridge	1	Loss of inverter	X		1 inv fail: none	1 inv fail: none	A three-inverter stand-by system will be used, thus preventing the loss of power due to a single inverter failure. Circuit analysis during development will determine feasibility of utilizing redundancy for critical items. A component improvement program should be initiated to improve the reliability since the failure of any component is detrimental to the inverter.
	2	Loss of inverter	X		2 inv fail: loss	2 inv fail: none	
	3	Loss of inverter	X		3 inv fail: loss	3 inv fail: loss	
	4	Loss of inverter	X				
Clock oscillator	1	Out of spec		Yes Δ	Same	Same	
	2	Loss of inverter	X				
	3	Loss of inverter	X				
	4	Out of spec		Yes Δ			
Digital countdown	1	Out of spec			Same	Same	
	2	Loss of inverter	X				
	3	Loss of inverter	X				
	4	Out of spec					
Transient voltage suppressor	1	Out of spec		Probably Δ	Same	Same	
	2	Out of spec		Possibly Δ			
	3	Loss of inverter	X				
	4	Out of spec		Possibly Δ			

Δ Dependent on nature of load as to harmonic sensitivity and wave distortion.

* Nature of malfunction

1 Series element short
2 Series element open
3 Shunt element short
4 Shunt element open

[redacted]

ENVIRONMENTAL CONTROL

SUBCONTRACTOR EFFORTS

Reliability efforts by the subcontractor on this subsystem during the third quarter of 1962 were devoted to the following major areas.

Reliability Design Reviews

Reliability design reviews were conducted as a continuing activity as designs approached completion. All subsystems and major environmental control system components and associated ground support equipment are subjected to design reviews.

Procurement and Engineering Specifications

Reliability support was provided on a continuous basis to establish reliability requirements and objectives for procurement and engineering specifications.

Trouble Reporting

The subcontractor, AiResearch, established a reliability data center that will be responsible for all manned-space-systems trouble reporting. Prior to the inception of this center, the reliability engineers in each program were solely responsible for successful implementation of the universal trouble reporting system (UTRS) employed by the subcontractor.

SYSTEM CHANGES

As of the conclusion of this reporting period, the environmental control system was in process of revision. The revision will include a 5.0-psia oxygen atmosphere instead of the dual gas (N_2 and O_2) atmosphere previously used and a simplified water management system. Because of reliability considerations, possible changes include the elimination of the gas analyzer, catalytic burner, triple-redundant components, air-lock components, and reentry oxygen supply, and the adoption of the wick-type water separator.

FAILURE-MODE ANALYSIS

Table 26 contains a failure-modes-and-effects analysis, performed at the component level to show effects on the system. Each component was analyzed to determine the various failures and the results these failures would have on both the system and mission. The analysis is the means of detecting failures and the action required. However, in some cases these columns have not been completed, pending instrumentation definition.

Most potential failures were analyzed at their extremes (e.g., valve failed to open or failed to close) with no intermediate condition considered. Critical component-port leakage in any given system was considered as a fail-open condition.

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis

Component	Failure Mode	Effect on Environmental Control System	Effect on Mission	Means of Detecting Failure	Corrective Action
Water separator check valve	Fail open	(A)(B)(C)* None	None	None	This is a parallel system providing a complete backup facility in case of primary failure
		(A)(B)** Loss of gas to suits if leak to cabin occurs (C)** Loss of conditioned gas to cabin	Abort	None	
	Fail closed	(A)(B)(C)* Loss of gas to suit or cabin	None	Drop in inlet pressure indication.	
		(A)(B)** Loss of gas to suits (C)** Loss of conditioned gas to cabin	None	Drop in inlet pressure indication	
Regenerative heat exchanger	Leakage, hot to cold	(A)(B)(C)* Reduction in cooling capacity and water removal	None, unless loss of tolerable temperature conditions; then abort.	By comparison of temperature indicators and position indicator	
	Leakage, hot to ambient (cabin)	(A)(C)* Reduction in cooling capacity and water removal. This condition causes an increased O_2 demand.	Abort	By comparison of temperature indicators and position indicator.	
		(B)* Loss of gas to suits	Abort		Don back pack, disconnect supply-and-return manifold, and repair leak.
	Leakage cold to ambient (cabin)	(A)(C)* Reduction in cooling capacity. This condition causes an increased O_2 demand.	Abort	By comparison of temperature indicators and position indicator	
		(B)*Loss of gas to suits	Abort		Don back pack, disconnect supply-and-return manifold and repair leak.

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

[redacted]

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on Environmental Control System	Effect on Mission	Means of Detecting Failure	Corrective Action
Suit circuit return check valve	Fail open (Cabin pressure, suit pressure)	(A)(C)* None	None	None	None
	Fail open (Cabin pressure, suit pressure	(B)* Loss of gas to suits	Abort	Increase ΔP indicator	Don back pack, disconnect supply-and-return manifolds.
	Fail closed	(A)(B)* None	None	None	None
		(C)* Loss of 0_2 makeup	Abort	Increase ΔP indicators	Don suits and connect suit circuit
Suit flow shutoff and limiting valve	Fail open	(A)(C)* None	None	None	Only used during boost, entry, and emergency conditions. One alternate inlet provided
		(B)* Loss of gas to suit	None; abort if two or more valves fail.	Open/close control inoperable	
	Fail closed	(A)(B)* Loss of gas to suit	None; abort if two or more valves fail.	Open/close control inoperable	
		(C)* None	None	None	
Suit flow return connector	Mechanical damage	(A)(B)(C)* None	None	Suit hose will not engage	
Suit manifold return check valve	Fail open	(A)(C)* None	None	None	None
		(B)* Loss of gas to suits.	None, unless two valves fail	Increased ΔP indication	Connect suit hose to failed-open connection
	Fail closed	(A)(B)* loss of gas flow to suit	None, unless two valves fail	Possible pressure buildup in suit	Connect suit hose to alternate connection
		(C)* None	None	None	None

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on Environmental Control System	Effect on Mission	Means of Detecting Failure	Corrective Action
Suit flow supply connection	Mechanical Damage	(A)(B)(C)* None	None	Suit hose will not engage	Use alternate connector
Debris trap	Main passage blocked	(A)(B)(C)* No debris removal facility	None	None	Trap contains a bypass
	** Bypass plugged	(A)(B)(C)** Loss of conditioned flow	Abort, unless corrective action is taken		Don back pack and clean or replace trap.
Catalytic filter	Filter system plugs	Increase in contamination of gas	Abort if contamination level exceeds specified limits	Gas analyzer	When contamination level exceeds specified limits cabin gas can be dumped.
	Heater elements inoperative	Increase in contamination of gas	Abort if contamination level exceeds specified limits	Gas analyzer	
Suit compressor	Compressor inoperative	(A)(B)(C)* Loss of gas flow	None, unless two compressors fail; then abort	Suit compressor ΔP indication and wattmeter	Use alternate compressor
	Compressor operating below required rpm	(A)(B)(C)* Reduction in gas flow	None, unless two compressors fail; then abort	Suit compressor ΔP indication and wattmeter	Use alternate compressor
Suit compressor	Burst	(A)(B)(C)* None, unless 1. (A)(C)* case fails to contain fragments.	1. Abort	Suit-compressor pressure indicator and oxygen-flow indicator.	Turn on alternate compressor.
		2. (B)* case fails to contain fragments.	2. Abort	Suit-compressor pressure indicator and wattmeter.	Don back packs.
		3. (A)(B)(C)** Damage to associated check valve (fail-open consideration only).	3. Abort	Possible pressure drop in indicator	Don back packs.

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

[redacted]

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on		Means of Detecting Failure	Corrective Action
		Environmental Control System	Mission		
Suit compressor check valve	Fail open (associated compressor operating)	(A)(B)(C)* None	Abort	None	None
	Fail open (associated compressor failed)	(A)(B)(C)** Loss of gas to cabin or suits	Abort	Inlet pressure indicator	None
	Fail closed	(A)(B)(C)* Associated compressor may overheat; also, a loss of gas to cabin or suits	None	Inlet pressure indicator	Use alternate compressor
		(A)(B)(C)** Associated compressor may overheat; also, loss of gas to cabin or suits	Abort if two valves fail closed	Inlet pressure indicator	Use alternate compressor
CO_2 and odor absorber isolation valve	Fail open	(A)(B)(C)* None	None	None	None
		(B)** Loss of gas to suits if a previous leakage failure, has occurred to CO_2 and odor absorber	Abort if replacement of CO_2 and odor absorber canister does not correct system-leakage condition.	None	None
	Fail closed	(A)(B)(C)* Loss of CO_2 and odor removal capacity	None	None	This condition will require a more frequent replacement of canister.
CO_2 and odor absorber check valve	Fail open	(A)(B)(C)* None	None		
		(B)** Loss of gas to suits if a previous leakage failure has occurred to CO_2 and odor absorber	Abort if replacement of CO_2 and odor absorber canister does not correct system leakage condition.	None	Don back packs and replace canister.

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

[redacted]

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on: Environmental Control System	Effect on: Mission	Means of Detecting Failure	Corrective Action
CO_2 and odor absorber check valve	Fail closed	(A)(B)(C)* Loss of CO_2 and odor removal capacity	None	Gas analyzer	This condition will require a more frequent replacement of canister in alternate leg of system.
CO_2 and odor absorber	Leakage to ambient (cabin)	(A)(B)(C)* None	None	Gas Analyzer	Replace faulty canister.
		(B)** Loss of gas to suits if a previous fail-open condition has occurred to valve	Abort if replacement of CO_2 and odor absorber canister doesn't correct system leakage condition.		Don back packs prior to replacing canister.
	Failure to remove CO_2	(A)(B)(C)* Failure to remove CO_2	None	Gas analyzer	Replace canister
Suit bypass control valve	Fail open	(A)(B)(C)* Reduction in suit flow	None	Inlet pressure indicator	Manual override provided on valve.
	Fail closed	(A)(B)(C)* Crew comfort slightly affected	None	Suit ΔP indicator	Manual override provided on valve
Suit compressor selector switch	Inoperative, contacts fused together	(A)(B)(C)* None	None	None	
		(A)(B)(C)** None	None	Wattmeter	Use alternate switch
	Inoperative, contracts broken	(A)(B)(C)* None	None	Wattmeter	Use alternate switch
Regenerative heat exchanger bypass valve	Actuator Fails	(A)(B)(C)* None	None	Temperature indicators and selector	Use manual override provided on valve
	Fails in total bypass position	(A)(B)(C)* Inlet temperature low	None	Temperature indicators and selector	Use manual override provided on valve
	Fails in total bypass closed position	(A)(B)(C)* Inlet temperature high	None	Temperature indicators and selector	Use manual override provided on valve

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on Environmental Control System	Effect on Mission	Means of Detecting Failure	Corrective Action
Glycol-to-suit air heat exchanger	Glycol to suit gas	(A)(B)(C)* Glycol contaminates suit circuit gas, loss of cooling	Abort	Gas analyzer	Open glycol bypass valve
	Glycol to ambient	(A)(C)* Contaminates cabin gas	Abort	Gas analyzer	Open glycol bypass valve
		(B)* Loss of coolant	Abort	Gas analyzer	Open glycol bypass valve
	Suit to ambient	(A)(C)* Loss of 0_2	Abort	Inlet pressure indicator	Don back packs
		(B)* Loss of 0_2	Abort	Oxygen supply flow indicator and inlet pressure indicator	Don back packs
Suit evaporator	Leakage, suit to steam (vacuum)	(A)(B)(C)* Loss of 0_2	Abort	Oxygen supply flow indicator	Use back packs
	Leakage, suit to cabin (ambient)	(A)(C)* Loss of 0_2	Abort	Oxygen supply flow indicator	
		(B)* Loss of 0_2	Abort	Oxygen supply flow indicator	Use back packs
Water separator diverter valve	Jamming in any position	(A)(B)(C)* Selection of either system impossible	No effect, unless previous failure has occurred	Manual control inoperative	
Water separator	Actuator inoperative	(A)(B)(C)* None, unless both actuators fail	Abort if both actuators fail	None	Use alternate system
	High H_20 back pressure	(A)(B)(C)* Water in 0_2 suit loop or cabin	Abort	Humidity indicator	Use back packs
	H_20-removal line blocked	(A)(B)(C)* Water in 0_2 suit loop or cabin	Abort	Humidity indicator	Use back packs
	Failure of system to remove H_20	(A)(B)(C)* Water in 0_2 suit loop or cabin	None	Humidity indicator	Use alternate system

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on		Means of Detecting Failure	Corrective Action
		Environmental Control System	Mission		
Suit air inlet temperature sensor	Sensor inoperative	(A)(B)(C)* Loss of automatic temperature regulation	None	Temperature indicators and personal comfort	Manual control on diverter valve
	Erratic operation	(A)(B)(C)* Loss of automatic temperature regulation	None	Temperature indicators and personal comfort	Manual control on diverter valve
Suit air temperature control	Control inoperative	(A)(B)(C)* Loss of automatic temperature control	None	Temperature indicators and personal comfort	Manual control on diverter valve
	Erratic operation	(A)(B)(C)* Loss of automatic temperature control	None	Temperature indicators and personal confort	Manual control on diverter valve
Suit evaporator temperature sensor	Sensor open or short circuited	(A)(B)(C)* If evaporator water control valve opened, loss of H_20 supply; if valve closed, loss of cooling capacity and H_20 removal.	None, if detected	Tank quantity indicator or temperature indicator	Manual override on evaporator water control valve
Suit evaporator air temperature control	Control inoperative	(A)(B)(C)* If evaporator water control valve opened, loss of H_20 supply; if valve closed, loss of cooling capacity and water removal	None, if detected	Temperature indicator or tank quantity indicator	Manual override on evaporator water control valve
	Erratic operation	(A)(B)(C)* Control searching valve will be oscillating, resulting in unnecessary wear-out, loss of H_20, loss of cooling capacity, and less H_20 removal.	None, if detected	Temperature indicator or tank quantity indicator	Manual override on evaporator water control valve.
Space radiator outlet check valve	Fail open	(A)(B)(C)* None, unless previous leakage failure has occurred	Abort	Outlet pressure indicator	Shutoff valves located next to disconnects
	Fail closed	(A)(B)(C)* None, unless 3 valves fail closed	None	Outlet pressure indicator	None

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on		Means of Detecting Failure	Corrective Action
		Environmental Control System	Mission		
Glycol pressure relief valve	Fail closed	(A)(B)(C)* Possible pressure buildup and rupture of radiator	Abort		
	Fail open	(A)(B)(C)* Loss of heat rejection	Abort		
Multiple quick disconnect	Fail open	(A)(B)(C)* None	None		Turn off manual valves prior to dropping service module
Manual shut-off valve	Fail closed	(A)(B)(C)* Loss of heat rejection by radiator	Abort	Temperature indicator and glycol quantity indicator	
	Fail open	(A)(B)(C)* No manual shutoff of glycol to radiator	None; backed-up when service module separated		
	Fail closed	(A)(B)(C)* No backup for valve	None		
	Fail open	(A)(B)(C)* Loss of glycol temperature control	None		Manual override on valve
Glycol check valve	Fail open (valve downstream of cabin heat exchanger)	(A)(B)(C)* During maximum cooling demand, no effect	None		None
		(A)(B)(C)* During maximum heating demand, glycol bypasses thermal load, and heating capacity is lost.	Suggest abort, although careful manipulation of valves could provide some control	Load outlet temperature indicator	Manually operate cabin heat exchanger temperature control valves
	Fail closed (valve downstream of cabin heat exchanger)	(A)(B)(C)* During maximum cooling demand, system flow is blocked.	Abort	Load outlet temperature indicator	Manually operate valves.
		(A)(B)(C)* During maximum heating demand, a loss of temperature control will result	Abort		Manually operate valves

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on Environmental Control System	Effect on Mission	Means of Detecting Failure	Corrective Action
Glycol check valve	Fail open (valve upstream of cabin heat exchanger)	(A)(B)(C)* During maximum cooling demand, glycol bypasses thermal load, and capacity is lost.	Abort	Load outlet temperature indicator	Manually operate valves
		(A)(B)(C)* During maximum heating demand no effect.	None	Load outlet temperature indicator	Manually operate valves
	Fail closed (valve upstream of cabin heat exchanger)	(A)(B)(C)* During maximum cooling demand, no effect.	None	None	None
		(A)(B)(C)* During maximum heating demand, system flow is blocked.	Abort	Load outlet temperature indicator	Manually operate valves
Glycol evaporator	Leakage, glycol to steam	(A)(B)(C)* Loss of coolant	Abort	Glycol reservoir quantity indicator	
	Glycol to cabin (ambient)	(A)(B)(C)* Loss of coolant	Abort	Gas analyzer	
	Cabin (ambient) to vacuum	(A)(B)(C)* Loss of 0_2	Abort	Cabin pressure indicator and oxygen supply flow indicator	Use back packs
Glycol reservoir	Leakage	(A)(B)(C)* Loss of glycol	Abort	Gas analyzer and glycol reservoir quantity indicator	Turn off appropriate valve, and relieve pressure from reservoir
	Spring fails	(A)(B)(C)* Loss of makeup glycol	None	None	Use manual backup
Glycol reservoir isolation valve	Fail open	(A)(B)(C)* No effect, unless previous leakage failure has occurred in reservoir	None, unless previous leakage failure, then abort		
	Fail closed	(A)(B)(C)** Loss of alternate system	Abort		

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on		Means of Detecting Failure	Corrective Action
		Environmental Control System	Mission		
Manual shutoff valve	Fail open	(A)(B)(C)* None, unless previous open failure occurred in connection	None, unless previous open failure, then abort		
	Fail closed	(A)(B)(C)* None	None		
Electronics-equipment temperature control valve	Jamming in any position	(A)(B)(C)* Loss of constant temperature controlled glycol to thermal load	Possible abort	Outlet temperature indicator	
Electronics-equipment glycol temperature control	Inoperative	(A)(B)(C)* Loss of automatic temperature control	Possible abort	Inlet temperature indicator	
	Erratic operation	(A)(B)(C)* Loss of automatic temperature control	Possible abort	Inlet temperature indicator	
Cabin heat exhanger temperature control valve	Jamming in any position	(A)(B)(C)* Loss of cabin temperature control	No effect, unless insufficient heat is removed from thermal load; then abort	Temperature indicators	(C) Don suits; manual override provided
Glycol pump check valve	Fail open	(A)(B)(C)* None, unless associated pump fails	None, unless associated pump fails, then abort		
	Fail closed	(A)(B)(C)* None, except that associated pump cannot be used	None	Temperature indicator	Use alternate system
Glycol pump	Inoperative, or erratic operation	(A)(B)(C)* None	None	Wattmeter	Use alternate system

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

CO[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on Environmental Control System	Effect on Mission	Means of Detecting Failure	Corrective Action
Glycol pump selector switch	Inoperative, contacts fused together	(A)(B)(C)* None	None		
		(A)(B)(C)** None	None	Wattmeter	Use alternate switch
	Inoperative, contacts broken	(A)(B)(C)* None	None	Wattmeter	Use alternate switch
Space radiator isolation and vent valve	Fail open	(A)(B)(C)* None	None		
		(A)(B)(C)** Loss of glycol if previous leakage failure has occurred in radiator	Abort	Glycol reservoir quantity indicator	
	Fail closed	(A)(B)(C)* Loss of one section of radiator	None	Outlet temperature indicator	Use alternate section
	Vent section fail open	(A)(B)(C) Loss of glycol	Abort	Glycol reservoir quantity indicator	
	Vent section fail closed	(A)(B)(C)* Pressure buildup allowable and possible radiator rupture	None	Outlet pressure indicator	Use alternate section
Glycol temperature control valve	Fail open	(A)(B)(C)* Loss of temperature-controlled glycol to exchanger	None	Temperature indicator and position indicator	Use manual override
	Fail closed	(A)(B)(C)* Loss of temperature-controlled glycol to exchanger	None	Temperature indicator and position indicator	Use manual override or alternate valve
Electronics-equipment glycol temperature sensor	Inoperative, or erratic operation	(A)(B)(C)* Loss of automatically temperature-controlled glycol to thermal load	Abort	Inlet temperature indicator	

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on: Environmental Control System	Effect on: Mission	Means of Detecting Failure	Corrective Action
Glycol temperature control	Inoperative, or erratic operation	(A)(B)(C)* Loss of automatically temperature-controlled glycol to exchanger	None, unless water supply is depleted because of erroneous demand		Manual override provided on valves
Glycol temperature sensor	Inoperative, or erratic operation	(A)(B)(C)* Loss of automatically temperature-controlled glycol to exchanger	None, unless water supply is depleted because of erroneous demand		Manual override provided on valves
Glycol fill and vent connection	Fail open	None	None	Loss of glycol after filling and before closing valve	Ground repair
	Fail closed	Inability to connect fill equipment during prelaunch	None		Ground repair
Cabin outflow pressure regulator and negative relief valve	Fail open	(A)(B)(C)* Loss of cabin pressurization	None	Cabin pressure indicator	Use manual override
	Fail closed	(A)(B)(C) Loss of backup valve	None		Alternate valve provided
Cabin heat exchanger	Leakage, glycol to ambient	(A)(B)(C)* Loss of coolant	Abort	Gas analyzer, and outlet and inlet temperature indicators	
Cabin temperature selector	Inoperative, or erratic operation	(A)(B)(C)* Loss of automatic cabin-temperature regulation	None	Temperature indicators	Manual override on valve
Cabin temperature anticipator	Inoperative, or erratic operation	(A)(B)(C)* Loss of automatic cabin-temperature regulation	None	Temperature indicator	Manual override on valve
Cabin temperature control	Inoperative, or erratic operation	(A)(B)(C)* Loss of automatic cabin-temperature regulation	None	Temperature indicators	Manual override on valve

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on: Environmental Control System	Effect on: Mission	Means of Detecting Failure	Corrective Action
Cabin temperature sensor	Inoperative, or erratic operation	(A)(B)(C)* Loss of automatic cabin-temperature regulation	None	Temperature indicator	Manual override on valve
Inflow snorkel	Snorkel deformed causing ball to plug inlet	(A)(B)(C)* None	None		
		(After reentry, if on land) None	None		Open hatch
		(After reentry, if on water) None	Loss of ventilation		Open hatch and evacuate capsule
	Snorkel fail open	(A)(B)(C)* None	None		Backup shutoff valve provided
		(After reentry, if on land) None	None		None
		(After reentry, if on water) None	None		Backup shutoff valve provided
Snorkel manual control inflow valve	Fail closed	(A)(B)(C)* None	None		
		(After reentry, if on land) None	None		Open hatch
		(After reentry, if on water) None	Loss of ventilation facility in event of extensive inhabitation requirement in capsule		Use O_2 from tank, if available
Outflow snorkel	Snorkel deforms causing ball to plug outlet	(A)(B)(C)* None	None		
		(After reentry, if on land) None	None		Open hatch
		(After reentry, if on water) None	Loss of ventilation		Open hatch and evacuate capsule
	Snorkel fails open	(A)(B)(C)* None	None		Backup shutoff valve
		(After reentry, if on land) None	None		

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

[redacted]

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on Environmental Control System	Effect on Mission	Means of Detecting Failure	Corrective Action
Outflow snorkel	Snorkel fails open	(After reentry, if on water) None	Possibly, a small amount of water will enter capsule		Back up shutoff valve
Snorkel manual control outflow valve	Fail closed	(A)(B)(C) None	None		
		(After reentry, if on land) None	None		Open hatch
		(After reentry, if on water) None	Loss of ventilation		Use O_2 from tank if available
Cabin recircu-lating blower diverter valve	Jamming in any position	(A)(C)* Inability to select alternate blower in event of blower failure	Abort		
Cabin recircu-lating blower selector switch	Inoperative contacts fused together	(A)(B)(C)* None	None	None	
		(A)(B)(C)** None	None	Wattmeter	Use alternate switch
	Inoperative contacts broken	(A)(B)(C)* None	None	Wattmeter	Use alternate switch
Cabin recircu-lating blower	Inoperative, or erratic operation	(A)(C)* If one blower fails during any phase, other than post landing, crew must replace blower.	Abort if two blowers fail	Wattmeter	Replace defective blower with spare carried on mission.
Nitrogen pressure relief valve	Fail open	(A)(B)(C)* Loss of N_2	Abort	Inlet pressure indicator	
	Fail closed	(A)(B)(C)* N_2 over-pressurization	None	Pressure indicators	Crack valve
Nitrogen inflow control and flow limiting valve	Fail open	(A)(B)(C)* Loss of N_2	None	Pressure indicator	Turn off manual override
		(A)(B)(C)* None	None		Alternate relief valve provided

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on		Means of Detecting Failure	Corrective Action
		Environmental Control System	Mission		
Nitrogen supply pressure regulating valve assembly	Fail open	(A)(B)(C)* Loss of N_2	None	Pressure indicator	
	Fail closed	(A)(B)(C)* Loss of N_2	None	Pressure indicator	
Oxygen inflow control valve	Fail open	(A)(B)(C)* Loss of 0_2 to cabin or suits	Abort	Gas analyzer	Control 0_2 supply using valve
	Fail closed	(A)(B)(C)* Loss of primary oxygen flow supply control	None	Gas analyzer	
		(A)(B)(C)** Loss of primary and secondary oxygen flow supply control	Abort	Gas analyzer	Use valve to control 0_2 supply
Oxygen inflow control	Inoperative, or erratic operation	(A)(B)(C)* 0_2 concentration variations or loss	None, unless control failure causes valve to remain open; then abort.	Gas analyzer	Use valves
Oxygen inflow control	Inoperative, or erratic operation	(A)(B)(C)* 0_2 concentration variations or loss	None, unless control failure causes valve to remain open; then abort.	Gas analyzer	Use valves
Oxygen partial pressure sensors Operating range 175-185 mm Hg	Failure in sensor induces open-demand to valve	(A)(B)(C)* Loss of 0_2 to cabin or suits	Abort	Gas analyzer	Control 0_2 supply using valve.
	Failure in sensor induces close-demand to valve	(A)(B)(C)* Loss of primary oxygen flow supply control	None	Gas analyzer	165-175-mm-Hg sensor backs up
Operating range 165-175 mm Hg	Failure in sensor induces open-demand to valve	(A)(B)(C)** Loss of secondary oxygen flow supply control	Abort	Gas analyzer	Control 0_2 supply using valve
	Failure in sensor induces close-demand to valve	(A)(B)(C)** Loss of secondary oxygen flow supply control	Abort	Gas analyzer	Control 0_2 supply using valve.

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

[redacted]

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on: Environmental Control System	Effect on: Mission	Means of Detecting Failure	Corrective Action
Oxygen storage tank	Leakage	(A)(B)(C)* None	None	Pressure indicator	
Oxygen fill port connection	Leakage	(A)(B)(C)* Loss of reentry 0_2	None	Bottle pressure indicator	
Oxygen storage tank valve assembly	Fail open	(A)(B)(C)* Loss of 0_2 from reentry tank	None	Tank pressure indicator	
	Fail closed	(A)(B)(C)* Loss of availability of reentry 0_2 tank	None		
Oxygen pressure regulating valve	Fail open	(A)(B)(C)* Loss of availability of reentry 0_2 tank	None		
Oxygen check valve	Fail open	(A)(B)(C)* No effect (During reentry, may damage pressure regulator because of allowable back up pressure when 0_2 tank is being used.)	None	None	None
	Fail closed	Loss of availability of reentry 0_2 tank	None	Pressure indicator	Alternate 0_2 system provided
Oxygen pressure relief valve	Fail open	(A)(B)(C)* Loss of 0_2 supply (During reentry) Loss of 0_2 supply	Abort	Flow indicator Pressure indicator	None
	Fail closed	(A)(B)(C)* None (During reentry, damage to downstream components)	None (None, assuming one oxygen inflow control valve fails open)		
Back-pack supply check valve	Fail open	None	None	None	None
	Fail closed	*Loss of 0_2 back-pack supply	No emergency backup supply.	None	None

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on Environmental Control System	Effect on Mission	Means of Detecting Failure	Corrective Action
Backpack-supply shutoff and pressure relief valve	Fail open (relief or shutoff)	Loss of backpack 0_2 supply.	No emergency back-up supply	None	None
	Fail closed (relief)	(A)(B)(C)* Possible over-pressurization of backpack 0_2 supply	None	None	None
	Fail closed (shut-off)	*Loss of capability to use backpack 0_2 supply	No emergency backup supply	None	None
Backpack supply cap	Jammed on	Loss of backpack fill capability	No emergency backup supply	None	
	Damaged and will not secure	None	None		
Manual oxygen supply shutoff valve	Fail open	(A)(B)(C)* None unless multiple quick disconnect leaks	None	None	None
	Fail closed	(A)(B)(C)* Loss of 0_2 supply	Abort		Use back packs
	Fail open	(A)(B)(C)* Loss of 0_2 supply by flooding system	Abort	Flow indicator	
	Fail closed	(A)(B)(C)* Loss of backup for oxygen inflow control valve and demand pressure regulator and relief valve	None	None	
Demand pressure regulator and relief valve	Fail open (regulator or relief)	(A)(B)(C)* Loss of 0_2	Abort	Flow indicator	None
	Fail closed (regulator or relief)	(A)(B)(C)* No effect	No effect, unless both fail; then abort		
Manual cabin-oxygen supply valve	Fail open	(A)(B)(C)* Loss of 0_2	Abort	Flow indicator	Shut off valve relocated downstream
	Fail closed	(A)(B)(C)* Inability to manually pressurize cabin, if reqd	None		

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on: Environmental Control System	Effect on: Mission	Means of Detecting Failure	Corrective Action
Oxygen-supply pressure regulating valve assembly	Fail open	(A)(B)(C)* Loss of 0_2, and downstream components subjected to high pressure	Abort	Pressure indicator and flow indicator	Partially close 0_2 valve to regulate 0_2
	Fail closed	(A)(B)(C)* Loss of 0_2	Abort	Flow indicator	
Emergency oxygen inflow control valve	Fail open	(A)(B)(C)* Loss of 0_2	Abort	Flow indicator	
	Fail closed	(A)(C)* No effect	None		None
		(B)* Inability to automatically flood cabin	Fail mission	Pressure indicator	Open manual cabin 0_2 supply valve
Water supply quick disconnect	Fail open	Loss of H_2O	Abort	None	None
Water check valve	Fail open	(A)(B)(C)* No effect	None	None	None
Downstream of multiple quick disconnect	Fail closed	(A)(B)(C)* Loss of makeup H_2O from fuel cell	Abort		
Downstream of potable water tank pressure relief valve	Fail open	(A)(B)(C)* Allows waste water mix with potable supply	None	Possible taste	Shut off potable water tank valve
	Fail closed	(A)(B)(C)* Loss of waste water for cooling	None	None	
Hot water supply valve	Fail open	(A)(B)(C)* Loss of potable water	Abort	Quantity indicator	None
	Fail closed	(A)(B)(C)* Loss of availability of hot water	None		
Potable water tank pressure relief valve	Fail open	(A)(B)(C)* Loss of potable H_2O	None	Quantity Indicator	Manual override provided on valve
	Fail closed	(A)(B)(C)* Loss of potable H_2O	None		Manual override provided on valve

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

[redacted]

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on: Environmental Control System	Effect on: Mission	Means of Detecting Failure	Corrective Action
Suit evaporator-water inflow control valve	Fail open	(A)(B)(C)* Loss of H_2O	None	Quantity indicator	Use H_2O from potable tank and manually operate valve
	Fail closed	(A)(B)(C)* Loss of cooling capacity	Abort	Temperature indicator	Manual override on valve
Glycol evaporator-water inflow control valve	Fail open	(A)(B)(C)* Loss of H_2O	Abort	Quantity indicator	Shut off manual override on valve
	Fail closed	(A)(B)(C)* Loss of cooling capacity	Abort	Temperature indicator	Manual override provided on valve
Freon shutoff valve	Fail open	(A)(B)(C)* No effect	None	None	None
	Fail closed	(A)(B)(C)* No freon cooling capability during prelaunch	None		Repair
Cold water supply valve	Fail open	(A)(B)(C)* Loss of potable water and water from fuel cell	Abort, if severe leakage	None	None
	Fail closed	(A)(B)(C)* No cold potable water available	None		
Water check valve	Fail open	(A)(B)(C)* Possible damage to fuel cell	Abort if fuel cell damaged	None	None
	Fail closed	(A)(B)(C)* Loss of potable water makeup and possible damage to fuel cell	Abort	None	None
Potable water tank	Bag rupture	(A)(B)(C)* Inability to expel H_2O from tank; also, possible 0_2 in H_2O supply	Abort	0_2 in H_2O supply	None
	Water leakage	(A)(B)(C)* Loss of potable H_2O	Abort	Quantity indicator	None

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on		Means of Detecting Failure	Corrective Action
		Environmental Control System	Mission		
Potable water tank pressure control and relief valve	Fail open to tank	(A)(B)(C)* Over-pressurize tank	Abort	Pressure indicator	
	Fail open to relief	(A)(B)(C)* Loss of 0_2	Abort	Pressure indicator	
	Fail closed	(A)(B)(C)* Inability to expel potable H_2O	Abort	Pressure indicator	
Freon quick disconnect	Fail open	(A)(B)(C)* None	None	None	
Water separator water check valve	Fail open	(A)(B)(C)* H_2O in suit circuit	Abort	Humidity indicator	Shut off water-fill valve
	Fail closed	(A)(B)(C)* Inability of separator to remove H_2O	No effect	Humidity indicator	Use alternate system
Water chiller	Leakage, water to ambient	(A)(B)(C)* Loss of potable H_2O	Abort		
	Leakage, glycol to water	(A)(B)(C)* Loss of potable H_2O and cooling capacity	Abort		
Waste water tank	Bag rupture	(A)(B)(C)* Inability to expel H_2O from tank; also, possible 0_2 in H_2O	Abort	0_2 in H_2O supply	
	Water Leakage	(A)(B)(C)* Loss of waste H_2O and cooling capacity	Abort	Quantity indicator	
Water fill valve	Fail open	(A)(B)(C)* No effect	None	None	
	Fail closed	(A)(B)(C)* Loss of availability of waste H_2O supply	Abort		Use potable water
Water vent valve	Fail open	(A)(B)(C)* Loss of potable H_2O	Abort	None	
	Fail closed	(A)(B)(C)* None	None		

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Table 26. Environmental Control System Failure - Mode Analysis (Cont)

Component	Failure Mode	Effect on		Means of Detecting Failure	Corrective Action
		Environmental Control System	Mission		
Waste water tank pressure control and relief valve	Fail open to tank	(A)(B)(C)* Overpressurize tank	Abort	Pressure indicator	
	Fail open to relief	(A)(B)(C)* Loss of O_2	Abort	Pressure indicator	
	Fail closed	(A)(B)(C)* Inability to expel waste H_2O	Abort	Pressure indicator	

(A) In suits, cabin pressurized
(B) In suits, cabin unpressurized
(C) In shirt sleeves

*Primary failure
**Secondary failure

~~CONFIDENTIAL~~

[redacted]

SUPERCRITICAL GAS STORAGE

RELIABILITY ANALYSIS

A reliability analysis of five supercritical-gas-storage configurations was performed to determine which system configuration would best meet reliability requirements. The five configurations evaluated are as follows:

1. A single oxygen system and a single hydrogen system supplying the electrical power system and the environmental control system.

2. A single oxygen system supplying the environmental control system and a single oxygen system with a single hydrogen system supplying the electrical power system.

3. Dual oxygen systems supplying the environmental control system and electrical power system, and a single hydrogen system supplying the electrical power system.

4. Dual oxygen and hydrogen systems supplying the environmental control system and the electrical power system.

5. Dual oxygen systems supplying the environmental control system and dual oxygen and hydrogen systems supplying the electrical power system.

Table 27 shows the component reliability values supplied by Beech Aircraft and used in this analysis. The reliability logic networks and mathematical models for these configurations are given in Figures 33 through 37.

RELIABILITY RESULTS

Results of the system analysis for the environmental control system, the electrical power system, and the individual system reliability requirements are given for each configuration in Table 28.

~~CONFIDENTIAL~~

Table 27. Supercritical Gas Storage Component Reliability Values

Component	Failure Rate (x10^6)	Failure Rate x Time* (x10^6)	Reliability
Fill Valve**	0.01	5.0	0.999995
Vent valve**	0.01	5.0	0.999995
Relief valve	0.10	50.0	0.999950
Tank	0.10	50.0	0.999950
Heat exchanger	0.10	50.0	0.999950
Control bypass valve	1.70	850.0	0.999150
Solenoid valve**	0.01	5.0	0.999995
Check valve	0.10	50.0	0.999950
Solenoid valve (latch)**	0.012	6.0	0.999994
Pressure switch	0.27	135.0	0.999865
Electric heater	0.10	50.0	0.999950
Capacity sensing probe	1.35	675.0	0.999325
Quantity switch	0.27	135.0	0.999865

* Time = 500 hours

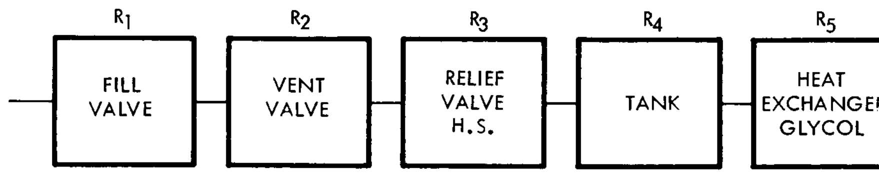
** Includes manual override

~~CONFIDENTIAL~~

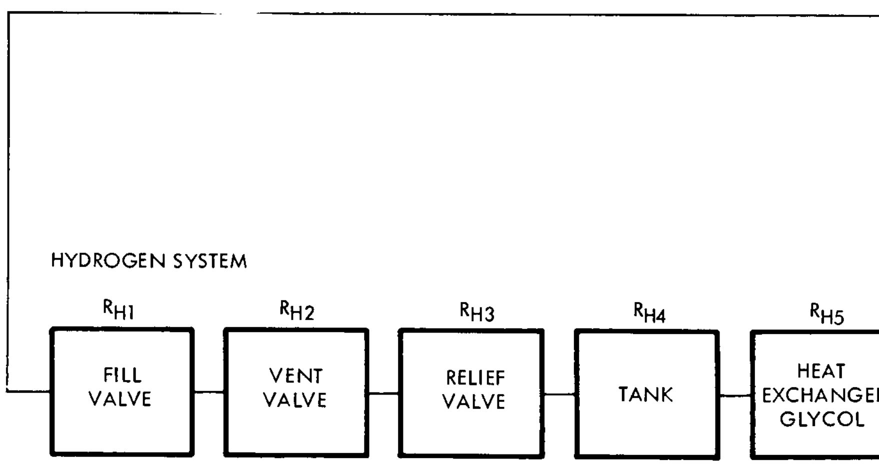
#1

~~CONFIDENTIAL~~

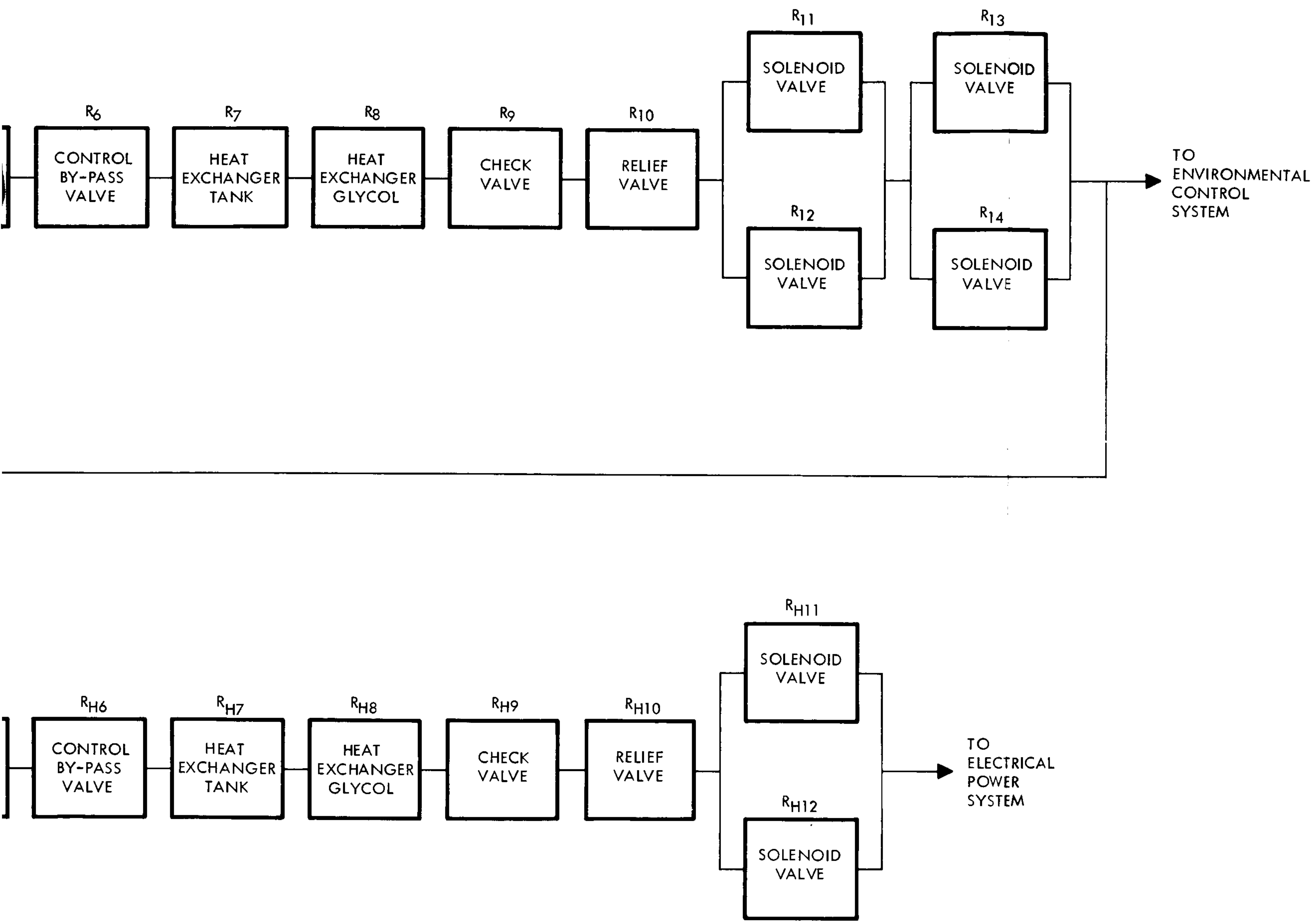
OXYGEN SYSTEM



HYDROGEN SYSTEM



#2



MATHEMATICAL MODEL, CONFIGURATION 1

$R_{\text{OXYGEN TO ENVIRONMENTAL CONTROL SYSTEM}}$

$$R_A = R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 \cdot R_6 \cdot R_7 \cdot R_8 \cdot R_9$$

$$R_A = 0.998840$$

$$R_B = R_{10} \left[1 - (1 - R_{11})(1 - R_{12})\right] \left[1 - (1 - R_{13})(1 - R_{14})\right]$$

$$R_B = 0.999950$$

$$R_{OXYGEN} = R_A \cdot R_B = (0.998840)(0.999950) = 0.998790$$

R_{HYDROGEN}

$$R_{AH} = R_{H1} \cdot R_{H2} \cdot R_{H3} \cdot R_{H4} \cdot R_{H5} \cdot R_{H6} \cdot R_{H7} \cdot R_{H8} \cdot R_{H9}$$

$$R_{AH} = 0.998840$$

$$R_{BH} = R_{H10} \left[1 - (1 - R_{H11})(1 - R_{H12})\right]$$

$$R_{BH} = 0.999950$$

$$R_{HYDROGEN} = R_{AH} \cdot R_{BH} = (0.998840)(0.999950) = 0.998790$$

$R_{\text{ELECTRICAL POWER SYSTEM}}$

$$R_{EPS} = R_{OXYGEN} \cdot R_{HYDROGEN}$$

$$= (0.998790)(0.998790) = 0.997581$$

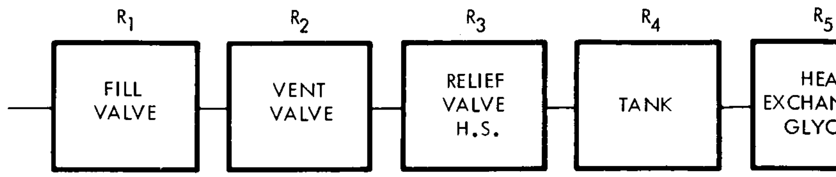
NOTE: SINGLE OXYGEN SYSTEM TO ENVIRONMENTAL CONTROL SYSTEM AND SINGLE OXYGEN AND SINGLE HYDROGEN SYSTEMS TO THE ELECTRICAL POWER SYSTEM

Figure 33. Supercritical Gas Storage Configuration 1 Logic Network and Mathematical Model

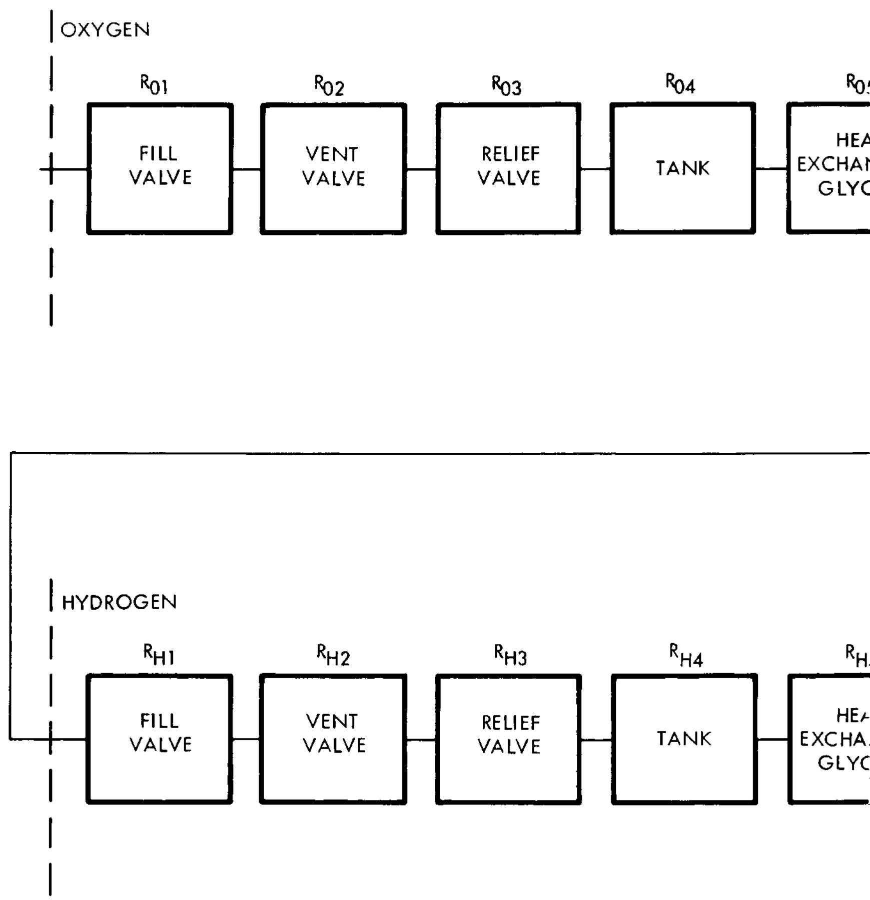
~~CONFIDENTIAL~~

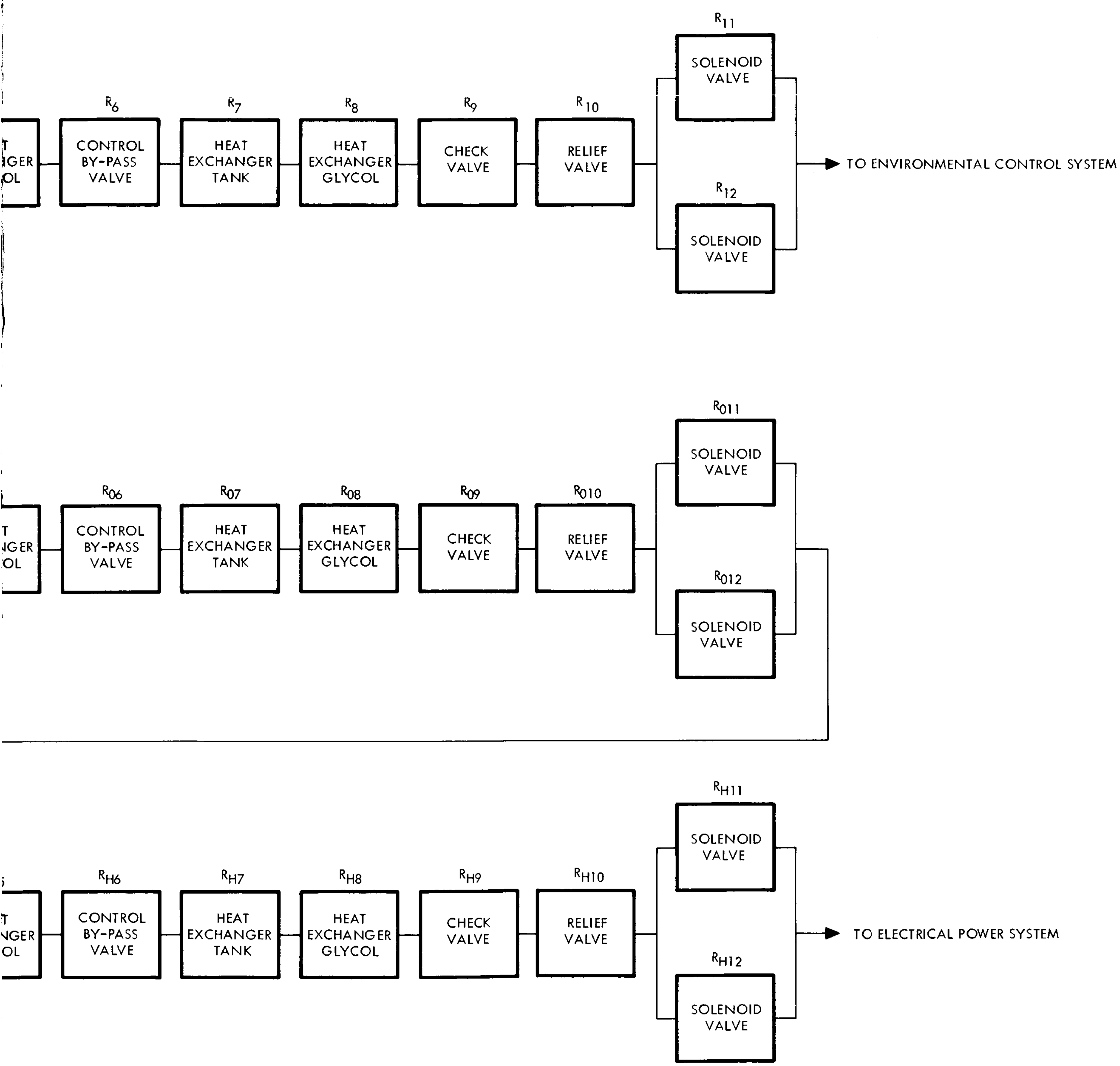
[redacted]

OXYGEN TO THE ENVIRONMENTAL CONTROL SYSTEM



OXYGEN AND HYDROGEN TO THE ELECTRICAL POWER SYSTEM





MATHEMATICAL MODEL, CONFIGURATION 2

OXYGEN TO ENVIRONMENTAL CONTROL SYSTEM

$R_A = R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 \cdot R_6 \cdot R_7 \cdot R_8 \cdot R_9$

$R_A = 0.998840$

$R_B = R_{10} \left[1 - (1 - R_{11})(1 - R_{12})\right]$

$R_B = 0.999950$

$R_{OXYGEN} = R_A \cdot R_B = (0.998840)(0.999950) = 0.998790$

HYDROGEN

$R_{AH} = R_{H1} \cdot R_{H2} \cdot R_{H3} \cdot R_{H4} \cdot R_{H5} \cdot R_{H6} \cdot R_{H7} \cdot R_{H8} \cdot R_{H9}$

$R_{AH} = 0.998840$

$R_{BH} = R_{H10} \left[1 - (1 - R_{H11})(1 - R_{H12})\right]$

$R_{BH} = 0.999950$

$R_{HYDROGEN} = R_{AH} \cdot R_{BH} = (0.998840)(0.999950) = 0.998790$

$R_{\text{ELECTRICAL POWER SYSTEM}}$

$R_{EPS} = R_{OXYGEN} \cdot R_{HYDROGEN}$

$= (0.998790)(0.998790) = 0.997581$

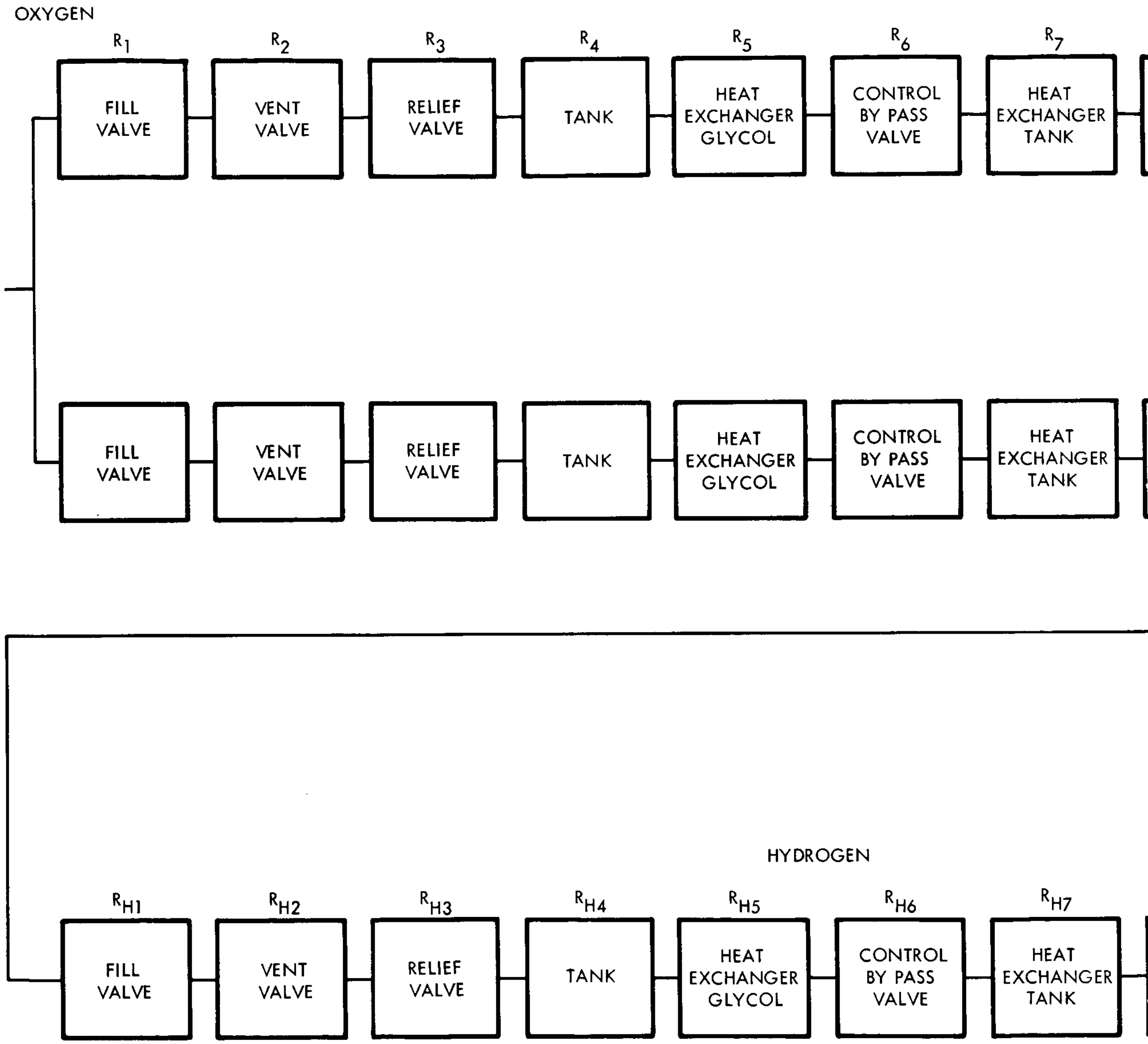
NOTE: SINGLE OXYGEN SYSTEM TO THE ENVIRONMENTAL CONTROL SYSTEM AND SINGLE OXYGEN AND HYDROGEN SYSTEM TO THE ELECTRICAL POWER SYSTEM.

Figure 34. Supercritical Gas Storage Configuration 2 Logic Network and Mathematical Model

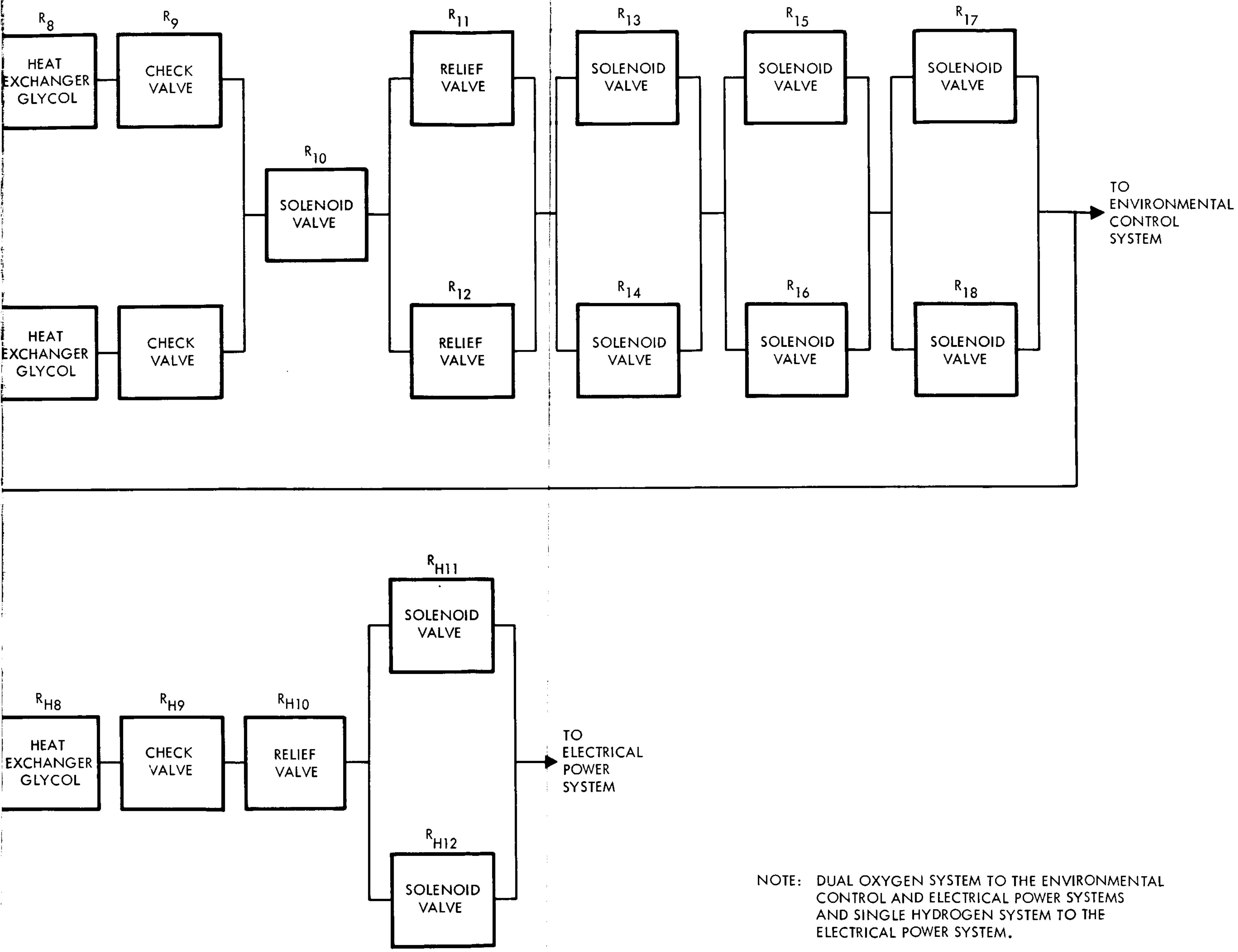
[redacted]

[redacted]

#1


OXYGEN
R_1
FILL VALVE
R_2
VENT VALVE
R_3
RELIEF VALVE
R_4
TANK
R_5
HEAT EXCHANGER GLYCOL
R_6
CONTROL BY PASS VALVE
R_7
HEAT EXCHANGER TANK
FILL VALVE
VENT VALVE
RELIEF VALVE
TANK
HEAT EXCHANGER GLYCOL
CONTROL BY PASS VALVE
HEAT EXCHANGER TANK
HYDROGEN
R_{H1}
FILL VALVE
R_{H2}
VENT VALVE
R_{H3}
RELIEF VALVE
R_{H4}
TANK
R_{H5}
HEAT EXCHANGER GLYCOL
R_{H6}
CONTROL BY PASS VALVE
R_{H7}
HEAT EXCHANGER TANK

#2



NOTE: DUAL OXYGEN SYSTEM TO THE ENVIRONMENTAL CONTROL AND ELECTRICAL POWER SYSTEMS AND SINGLE HYDROGEN SYSTEM TO THE ELECTRICAL POWER SYSTEM.

MATHEMATICAL MODEL, CONFIGURATION 3

$R_{\text{OXYGEN TO ENVIRONMENTAL CONTROL SYSTEM}}$

$R_A = R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 \cdot R_6 \cdot R_7 \cdot R_8 \cdot R_9$

$R_A = 0.998840$

$R_B = R_{10} \left(\left[1 - (1 - R_{11})(1 - R_{12})\right] \left[1 - (1 - R_{13})(1 - R_{14})\right] \left[1 - (1 - R_{15})(1 - R_{16})\right] \left[1 - (1 - R_{17})(1 - R_{18})\right]\right)$

$R_B = 0.999994$

$R_{OXYGEN} = \left[2R_A - (R_A)^2\right] R_B$

$= 2(0.998840) - (0.998840)^2 \times (0.999994) = 0.999993$

R_{HYDROGEN}

$R_{AH} = R_{H1} \cdot R_{H2} \cdot R_{H3} \cdot R_{H4} \cdot R_{H5} \cdot R_6 \cdot R_7 \cdot R_8 \cdot R_9$

$R_{AH} = 0.998840$

$R_{BH} = R_{H10} \left[1 - (1 - R_{H11})(1 - R_{H12})\right]$

$R_{BH} = 0.999950$

$R_{HYDROGEN} = R_{AH} \cdot R_{BH} = (0.998840) \cdot (0.999950) = 0.998796$

$R_{\text{ELECTRICAL POWER SYSTEM}}$

$R_{EPS} = R_{OXYGEN} \cdot R_{HYDROGEN}$

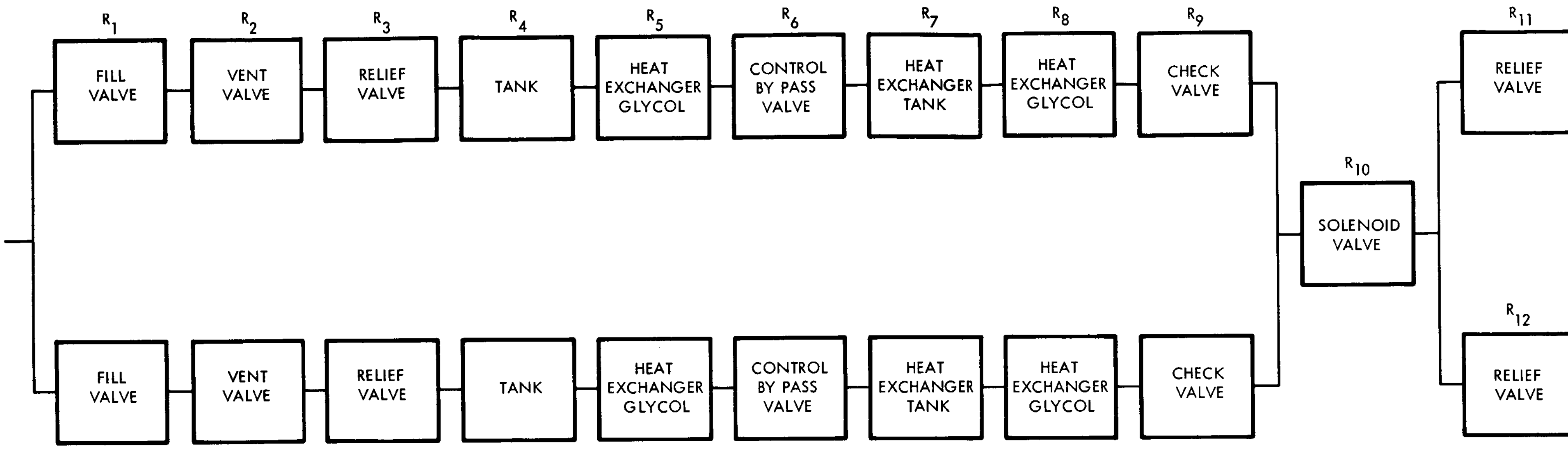
$= (0.999993)(0.998790) = 0.998783$

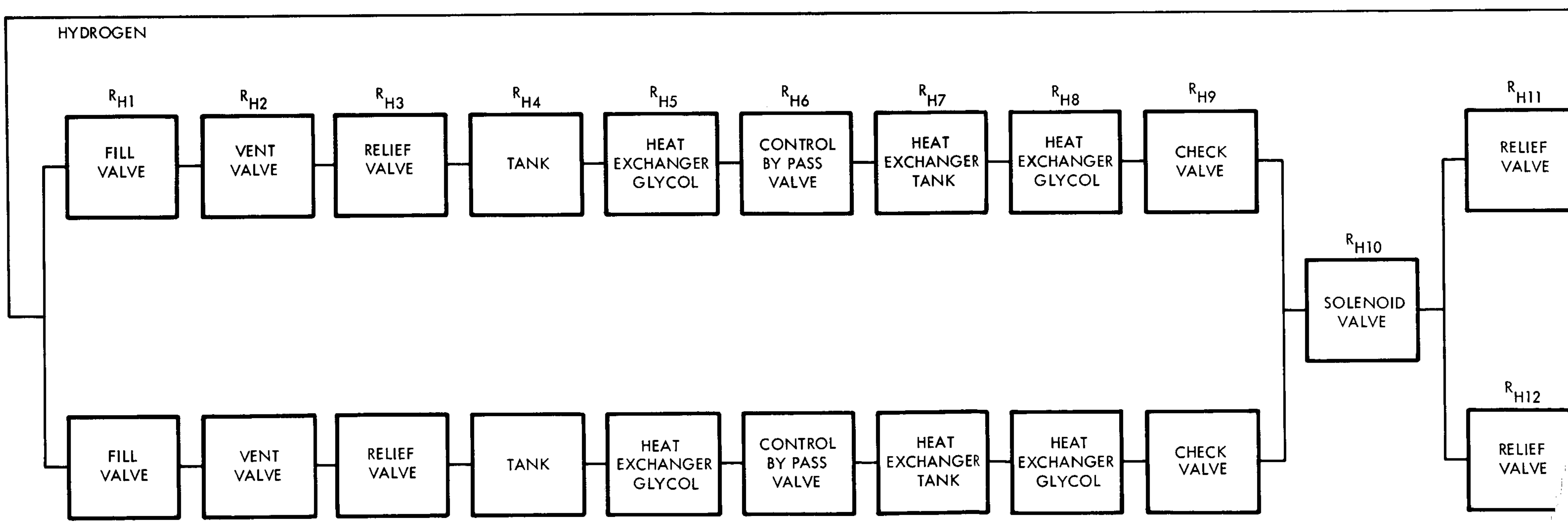
Figure 35. Supercritical Gas Storage Configuration 3 Logic Network and Mathematical Model

[redacted]

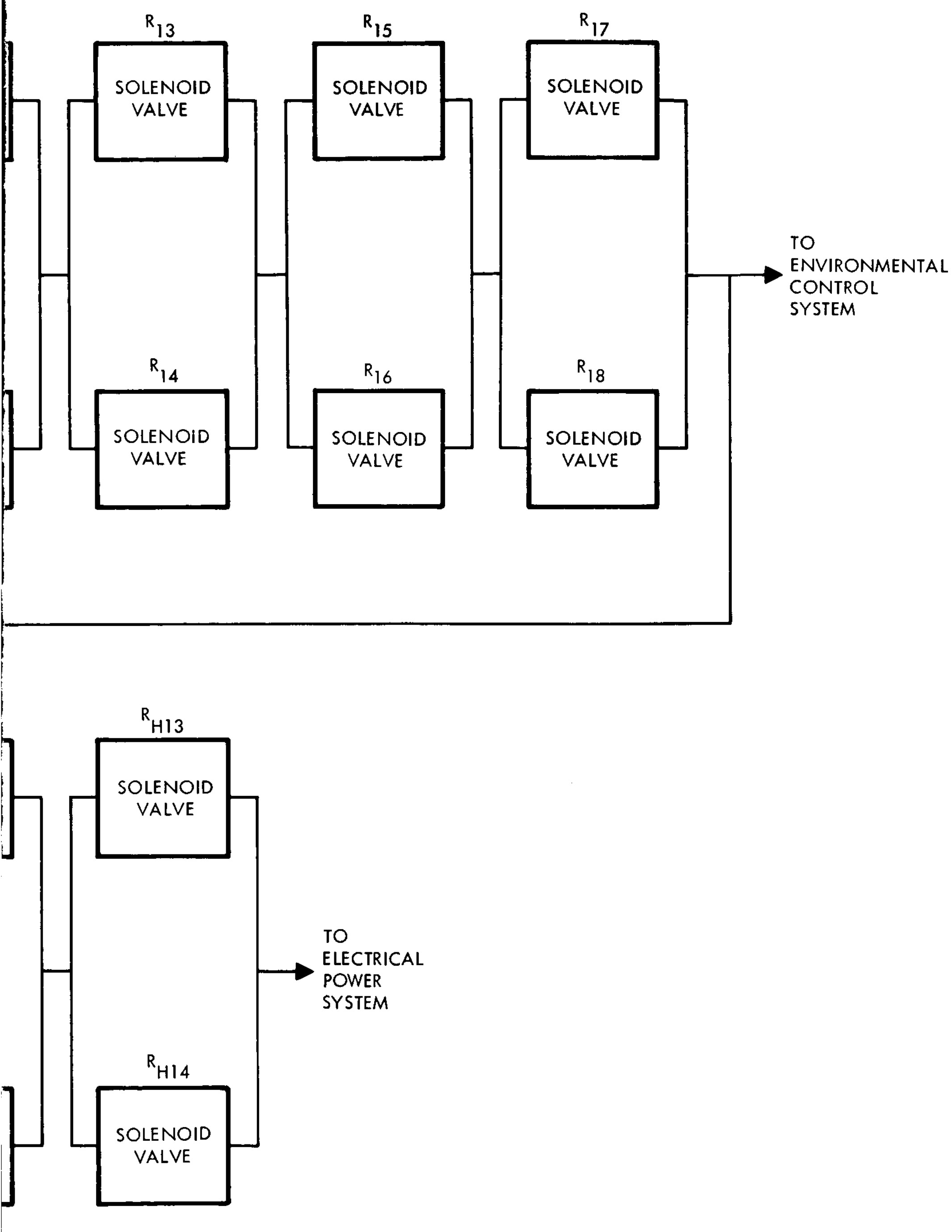
#1

OXYGEN





#2



MATHEMATICAL MODEL, CONFIGURATION 4

OXYGEN TO ENVIRONMENTAL CONTROL SYSTEM

$$R_A = R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 \cdot R_6 \cdot R_7 \cdot R_8 \cdot R_9$$

$$R_A = 0.998840$$

$$R_B = R_{10} \left(\left[1 - (1 - R_{11})(1 - R_{12})\right] \left[1 - (1 - R_{13})(1 - R_{14})\right] \left[1 - (1 - R_{15})(1 - R_{16})\right] \left[1 - (1 - R_{17})(1 - R_{18})\right] \right)$$

$$R_B = 0.999994$$

$$R_{OXYGEN} = 2 R_A - (R^2{}_A) \cdot R_B$$

$$= 2\,(0.998840) - (0.998840)^2\ (0.999994)$$

$$= 0.999993$$

HYDROGEN

$$R_{AH} = R_{H1} \cdot R_{H2} \cdot R_{H3} \cdot R_{H4} \cdot R_{H5} \cdot R_{H6} \cdot R_{H7} \cdot R_{H8} \cdot R_{H9}$$

$$R_{AH} = 0.998840$$

$$R_{BH} = R_{H10} \left[1 - (1 - R_{H11})(1 - R_{H12})\right] \left[1 - (1 - R_{H13})(1 - R_{H14})\right]$$

$$R_{BH} = 0.999994$$

$$R_{HYDROGEN} = 2 R_{AH} - (R^2{}_{AH}) \cdot R_{BH}$$

$$= 2\,(0.998840) - (0.998840)^2\ (0.999994)$$

$$= 0.999993$$

ELECTRICAL POWER SYSTEM

$$R_{EPS} = R_{OXYGEN} \cdot R_{HYDROGEN}$$

$$= (0.999993)(0.999993)$$

$$= 0.999986$$

NOTE: DUAL OXYGEN AND DUAL HYDROGEN SYSTEMS SUPPLYING THE ENVIRONMENTAL CONTROL SYSTEM AND THE ELECTRICAL POWER SYSTEM

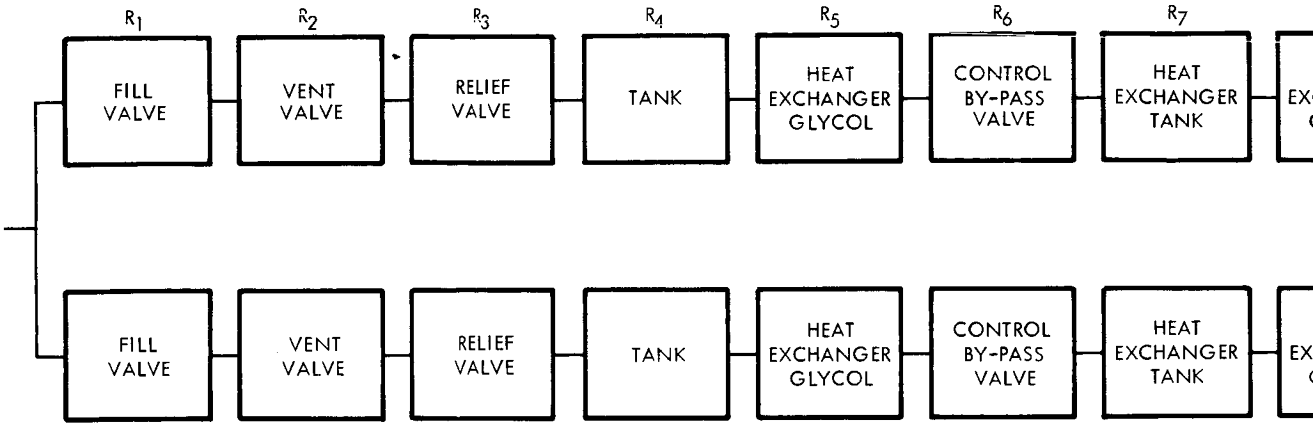
Figure 36. Supercritical Gas Storage Configuration 4 Logic Network and Mathematical Model

[redacted]

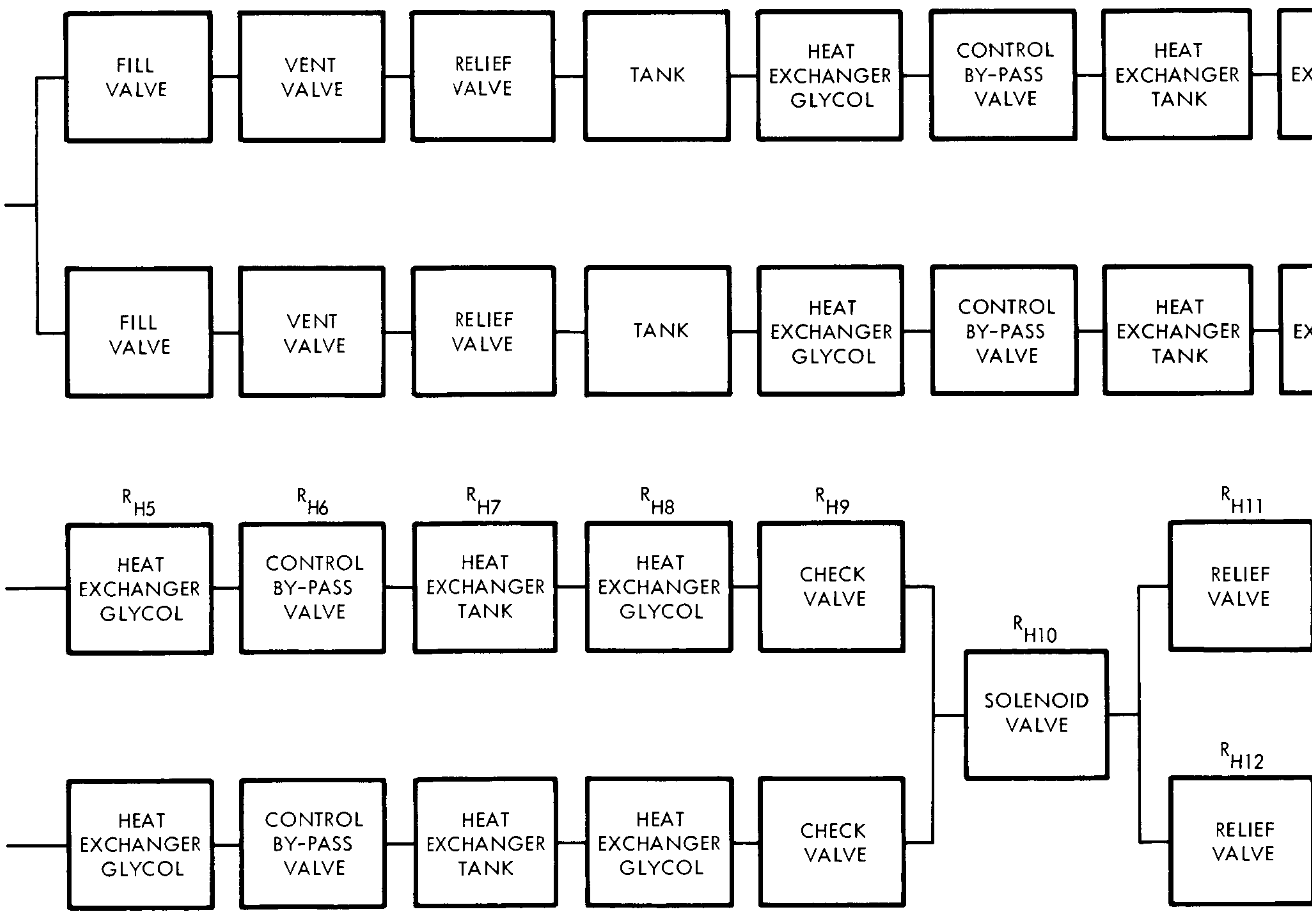
[redacted]

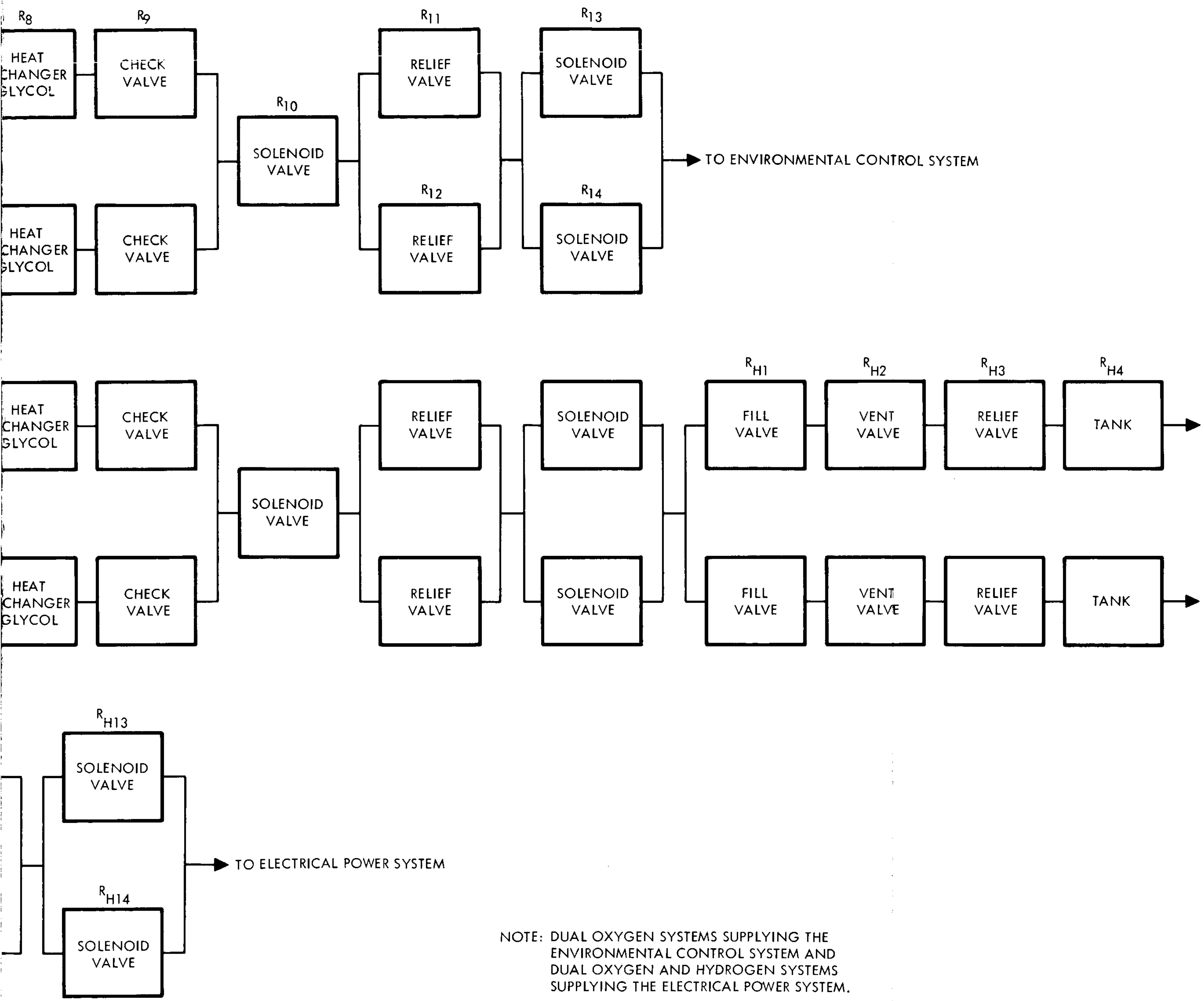
#1

OXYGEN TO THE ENVIRONMENTAL CONTROL SYSTEM



OXYGEN AND HYDROGEN TO THE ELECTRICAL POWER SYSTEM





NOTE: DUAL OXYGEN SYSTEMS SUPPLYING THE ENVIRONMENTAL CONTROL SYSTEM AND DUAL OXYGEN AND HYDROGEN SYSTEMS SUPPLYING THE ELECTRICAL POWER SYSTEM.

MATHEMATICAL MODEL, CONFIGURATION 5

OXYGEN TO THE ENVIRONMENTAL CONTROL SYSTEM

$$R_A = R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 \cdot R_6 \cdot R_7 \cdot R_8 \cdot R_9$$

$$R_A = 0.998840$$

$$R_B = R_{10} \left[1 - (1 - R_{11})(1 - R_{12})\right] \left[1 - (1 - R_{13})(1 - R_{14})\right]$$

$$R_B = 0.999994$$

$$R_{OXYGEN} = 2\,R_A - (R_A)^2 \cdot R_B$$

$$= 2\,(0.998840) - (0.998840)^2\,(0.999994)$$

$$= 0.999993$$

ELECTRICAL POWER SYSTEM

$$R_{OXYGEN} = R_{HYDROGEN} = 0.999993$$

$$R_{EPS} = R_{OXYGEN} \cdot R_{HYDROGEN}$$

$$= 0.999986$$

Figure 37. Supercritical Gas Storage Configuration 5 Logic Network and Mathematical Model

Table 28. Supercritical Gas Storage Reliability Comparison

System	Configurations (failures per million)					
	1	2	3	4	5	Required
O_2 supply to environmental control system	1210	1210	7	7	7	10
O_2 and H_2 supply to electrical power system	2419	2419	1217	14	14	20

Configurations 1 and 2 do not meet either the environmental control subsystem or the electrical power subsystem reliability requirements. Configuration 3 would meet environmental control reliability requirements, but it would not meet electrical power reliability requirements.

Configurations 4 and 5 meet both the environmental control and the electrical power reliability requirements. There is a weight penalty involved in the use of configuration 5. The equivalent reliabilities of 4 and 5 are a result of 5 having no crossfeed capability between the oxygen systems.

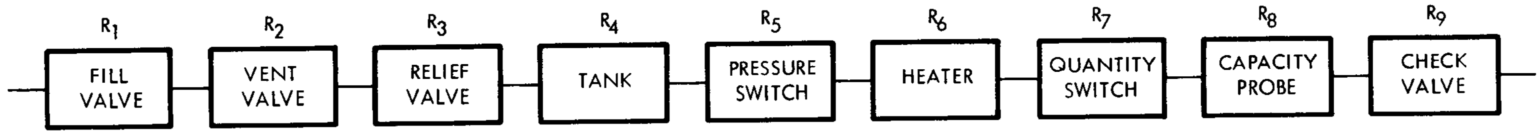
The 500-hour operating life includes prelaunch operations for the supercritical gas storage subsystem. A brief analysis was performed on a single-tank system employing a dual distribution system with quadruple check valves. This system does not provide the apportioned reliability for the environmental control system supply. A failure in the tank could constitute a catastrophic failure mode resulting in loss of crew and spacecraft.

The findings of this study are conclusive that configuration 4 is the best configuration of the five.

ELECTRICAL HEATER ANALYSIS

A reliability analysis was performed to evaluate the effects of electrical heaters on configuration 4. It was proposed that electric heaters be used in lieu of the glycol heat-exchanging system to maintain system storage pressure. The supply system was revised to replace the internal heat exchanger and the external glycol heat exchanger with a pressure switch, an internal electric heater, a quantity switch, and a capacity probe. Results showed that the electrical heater system would meet the required system reliability. Figure 38 shows the system logic network, the mathematical model, and the calculated system reliability.

SUBSYSTEM $\boxed{A}$ RELIABILITY OF OXYGEN SYSTEM



$R_A = R_{OXYGEN\ SUBSYSTEM}$

$R_A = R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 \cdot R_6 \cdot R_7 \cdot R_8 \cdot R_9$

$R_A = 0.998845$

$R_A = R_{OXYGEN\ SUBSYSTEM} = R_{HYDROGEN\ SUBSYSTEM}$

RELIABILITY OF REDUNDANT OXYGEN SYSTEM

$R_{SYSTEM} = \left[2\,(R_A) - (R_A)^2\right] \cdot R_{SOLENOID\ VALVE}$

$R_{SYSTEM} = \left[2\,(0.998845) - (0.998845)^2\right] \cdot (0.999994)$

$R_{SYSTEM} = 0.999992$ = 8 FAILURES PER MILLION MISSIONS

RELIABILITY OF TOTAL OXYGEN HYDROGEN STORAGE SYSTEM

$R_{TOTAL} = R_{OXYGEN} \cdot R_{HYDROGEN}$

$R_T = (0.999992)(0.999992)$

$= 0.999984$ = 16 FAILURES PER MILLION MISSIONS

Figure 38. Electrical Heater, Supercritical Gas Storage, Logic Network

SPECIAL STUDIES

HEAT SHIELD

The design review of available drawings and test procedures for heat shields was initiated with respect to structural integrity, reliability, and backface-temperature limits.

A study of two approaches to the nondestructive measurement of bond strength was begun.

The tensile-load ultrasonic technique incorporates standard ultrasonic equipment, combined with a tensile load placed on the test specimen while the measurements are being made.

The electromagnetic-induced radiation energy technique utilizes electromagnetic propagation as the means of investigation.

An IBM computer program was written to assist in the statistical analysis of experimental data to be generated in the materials research program related to reliability measurement and prediction. Computer outputs will include analyses of variance statistics, mean and variance estimates, statistical tolerance limits, homogeneity of variance tests, and other useful calculations.

In connection with an experimental testing procedure, a statistical procedure has been developed for the purpose of deriving simultaneous confidence levels of specific heat and thermal conductivity properties of Apollo ablative materials.

Current structural analyses of the heat shield are being restricted to those problem areas which indicate that changes in the heat-shield substructure design may be necessary in order to meet mission requirements. In all cases, the heat shield is being analyzed as an ablator-substructure composite, not as a substructure alone, to determine the influence of the substructure on the ablator, and vice versa. All of the critical problem areas now being investigated are concerned with the effects of coldsoak conditions; and effects of stringers, frames, and an ejection panel cutout on the ablator and honeycomb substructure. Preliminary analysis indicates that at command module station 82.75, both the Avcoat 5026 ablator and the fiberglass stringer are overstressed when the heat shield is at a temperature of -260 F. This situation is not overcome by increasing the coldsoak temperature to -150 F.

[redacted]

An analytical program has been drawn up and is being executed to determine fastener loads, fastener spacing and location, ablator-tile stresses due to fastener loads, and effects of fastener spacing on ablator-tile buckling during entry.

A two-hour coldsoak test to -260 F of a 0.10 by 12 by 12-inch tile bonded with Eccosil 4640 (silicone rubber) adhesive to representative steel honeycomb sandwich substructure was performed with no resulting failure. Holes were then cored through the tile and substructure, and the specimen was again subjected to the coldsoak with no failure.

Results of ultrasonic testing of materials and adhesives are being correlated to obtain information for forthcoming test procedures.

Considerable emphasis was placed on theoretical and experimental evaluation of the many thermal and structural discontinuities in the command module heat shield. Preliminary analyses of fasteners, ablator-edge restraint techniques, access door designs, shear ties, and tension ties have been completed. Complete, detailed results are not available. The analysis points out that it may be possible to tolerate some of these discontinuities, providing certain modifications are incorporated in the design. Basically, these design modifications require disturbing the aerodynamic contour or indenting the substructure. At the present time, it is not possible to assess all the merits and demerits of these two procedures. This will be attempted after a more detailed analysis of the heat shield composite has been completed.

PROBABILITY DISTRIBUTION OF EQUILIBRIUM-DESCENT VELOCITY

Air-Density Variation

Both crew safety and mission success are affected by the command module's vertical impact velocity on its return to earth. Therefore, it is necessary to investigate the probability distribution of equilibrium-descent velocity based on air-density variation. (The effects of other variables, i.e., wind gusts, air currents, etc.; will be considered in future studies.) Parachute and command module structural design criteria will be established as a result of an investigation of the vertical-impact velocity distribution.

The results of a study of the USAF Parachute Handbook and references on atmospheric density profile, earth landing impact attenuation, and effects of module-weight increase on the parachute system are summarized in Table 29. The probability of attaining the minimum, median, and maximum descent velocities for various numbers of parachutes open, parachute diameters, and command module weights is presented.

[redacted]

Table 29. Command Module Descent Parameters

Number of Parachutes Open	Command Module Weight (pounds)	Diameter of Parachute (feet)	Maximum velocity* (ft/sec)	Probability of Attaining Maximum Velocity (percent)	Median Velocity** (ft/sec)	Probability of Attaining Median Velocity (percent)	Minimum Velocity*** (ft/sec)	Probability of Attaining Minimum Velocity (percent)
2	9,000	85	31.01	14	30.39	50	28.91	99.98
	9,250	85	31.44		30.81		29.31	
	9,500	85	31.86		31.22		29.87	
	9,000	88	29.81		29.36		27.92	
	9,250	88	30.36		29.72		28.32	
	9,500	88	30.78		30.17		28.70	
	9,000	92	28.63		28.07		26.70	
	9,250	92	29.02		28.45		27.07	
	9,500	92	29.41		28.84		27.43	
3	9,000	85	25.31	16	24.81	50	23.60	99.98
	9,250	85	25.66		25.15		23.93	
	9,500	85	26.01		25.49		24.25	
	9,000	88	24.45		23.96		22.80	
	9,250	88	24.34		24.26		22.79	
	9,500	88	25.12		24.62		23.42	
	9,000	92	23.39		22.92		21.81	
	9,250	92	23.71		23.24		22.11	
	9,500	92	24.03		23.55		22.40	

* Based on observed minimum air density data.
** Based on observed median air density data.
*** Based on observed maximum air density data.

[redacted]

As an example, when two 85-foot parachutes are used on a 9000-pound command module, the maximum, median, and minimum velocities are 31.01, 30.39, and 28.91 feet per second, respectively, and the associated probabilities of exceeding each are 0.14, 0.50, and 0.9998, respectively.

Methods of Computation

The rate of descent of a parachute is given by:

$$\text{Rate of descent, } V = \sqrt{\frac{2\,W}{C_D \cdot A \cdot \rho}}$$

in which

W = command module weight

C_D = drag coefficient

A = parachute area

ρ = air density

Using the known air-density-probability distribution, the corresponding velocity-probability distributions can be determined.

COMMAND MODULE TO SERVICE MODULE ELECTRICAL CONNECTION

Reliability engineering conducted a preliminary study on the proposed umbilical connector designs for the service module to command module electrical connections. This study compared the reliability characteristics of a single umbilical concept to those of a dual umbilical concept. From a reliability standpoint, the dual umbilical concept proved to be superior, as circuits which are essential for crew safety may be routed through both connectors.

BATTERY SUBSYSTEM

A reliability analysis was performed to establish a numerical reliability goal for the individual battery. In the battery subsystem, it is required that two of the three batteries operate in order to insure mission success and crew safety. The battery subsystem reliability requirement has been apportioned at 0.99999 (10×10^{-6} allowable failures) for mission success. It was determined that, in order to meet this requirement, individual battery reliability must be 0.9984 (1600×10^{-6} allowable failures per mission).

[redacted]

REACTANT SUPPLY SYSTEM

During this reporting period, various design changes resulted in the incorporation of an additional cross-feed network in the hydrogen supercritical storage portion of the reactant supply system. Due to this change, reliability engineering determined that prior reliability requirements could be reduced. The relaxing of these requirements permitted the removal of two 3-way squib valves, two check valves, and all associated fittings and piping.

Implementation of these changes did not result in a degradation of system reliability. The overall reactant supply system reliability was maintained in excess of 0.99999.

[redacted]

III. SYSTEM AND SUBSYSTEM TEST ACTIVITY

SYSTEM

GENERAL TEST PLANNING

Recent cost-reduction and schedule-adjustment exercises resulted in the deletion of many of the proposed systems tests, both from the spacecraft program and, more particularly, from the boilerplate program. Objectives call for demonstrating reliability at the system level before the first lunar flight.

Reliability engineering has recognized the above as a problem area and has begun a study effort to define the problem and determine corrective action required. In order to implement this study, a task force composed of the most capable engineers from the reliability test group, system integration, quality engineering, and system test has been formed. The result of this study will provide the following data regarding qualification-reliability demonstration at the system level.

Expected reliability and confidence levels at the time of the first manned flight,

Articles and interfaces yet to be fully qualified at the time of the first manned flight

Additional test requirements to fully qualify all articles and interface at the system level.

Additional tests required to provide minimum reliability assessment, i.e., at least 60 percent confidence that the proposed mission can be accomplished with a full-system reliability of the 0.96 objective.

Additional tests required to demonstrate the full program objectives of a reliability of 0.96 with 90-percent confidence, but then only for the specific mission proposed.

It is expected that the foregoing effort will be completed within the next quarter, and will be updated on a continuing basis thereafter.

SPACECRAFT TESTS

During this quarter no qualification or reliability testing as such was attempted; however, development tests of boilerplate articles are underway. As the data will contribute to the total assessment of system reliability demonstration, reliability engineers took an active part in these tests. The tests accomplished to date were limited to:

A total of three water-impact tests using boilerplate number 1, the data from which is presently being processed and will be recorded in a subsequent report. Additional tests of this nature are planned for the next quarter.

A total of 17 water-recovery and handling-equipment development tests using boilerplate number 25. These included drop tests, flotation tests, and towing tests, all under a wide variety of conditions. The data from these tests are also in process; the series is considered complete, and the vehicle has been shipped to NASA.

[redacted]

SUBSYSTEM

ENVIRONMENTAL CONTROL

Reliability Test Plan (SS-1004-R)

The material in this document is being revised in accordance with the changes requested by S&ID. This document will be incorporated into the over-all test plan and will become a permanent section in that document. Included in the revision will be a more comprehensive treatment of the environmental test conditions to exactly define the separate and combined environments for each equipment-item test. In addition, the method employed to demonstrate reliability and the statistical treatments will be discussed in more detail.

Overall Test Plan (SS-1001-R)

A major revision to this document is being prepared in accordance with changes requested by S&ID. The revision will describe all development testing, including separate and combined environment tests to be performed on all equipment and components. It will also contain details of the qualification and reliability tests previously described by AiResearch in SS-1004-R.

Prototype Subsystem Test Progress

Basic test requirements for the environmental control subsystem prototype are being established and incorporated into a test procedure. Component fabrication and procurement schedules are being revised on a continuous basis.

SUPERCRITICAL GAS STORAGE

Development Tests

Development results were obtained on tests associated with minimum titanium-tube bending, welding techniques, and insulation back-up. A development program for the initiation of burst-testing of titanium and Inconel-X17 pressure vessels was started. Insulation vibration-testing has been conducted to verify structural integrity of the insulation.

[redacted]

Specification Reviews

The Beech reliability group has reviewed and commented on procurement specifications for the oxygen module, hydrogen modules, quick disconnects, cross-feed lines, and check valves; and their suggested revisions have been incorporated.

FUEL CELLS

Qualification-Reliability Test Plan

Pratt & Whitney's qualification-reliability test plan, as revised 3 August 1962, was reviewed by S&ID, and comments were submitted to them on 18 September. The general philosophy of the document is acceptable, but changes were required in the mission-simulation tests, and will be incorporated in a document revision.

Qualification-reliability testing of the fuel-cell powerplant is not scheduled to begin until November 1963.

Design and Development Testing

Design and development testing started in August 1962 on a few component parts. Development testing of an independent fuel cell module was scheduled to start October 1962. During the next quarter the development testing of all component parts except the preheaters and the radiator loop pump motor will have begun.

MISSION PROPULSION

Qualification-Reliability Test Plan

The initial Qualification-Reliability Test Plan (3865-11) was submitted by Aerojet on 6 July 1962. The test plan was found unacceptable, as the detailed methods to be employed in qualifying the rocket engine were not included. The plan basically covered the methods to be used in the statistical evaluation of test data, but it did not adequately cover the test conditions.

The first revision to the the Qualification-Reliability Test Plan (3865-11A) was submitted by Aerojet on 6 September 1962. The test plan satisfactorily encompassed the overall test methods, sequence of tests, and statistical evaluation techniques to be used during the test program. As a result of omissions regarding the reporting procedures to be used and other pertinent detailed information, the qualification-reliability test plan is to be revised again prior to formal approval.

[redacted]

Qualification-reliability testing is presently scheduled to commence in the latter part of 1963.

Development Tests

During this reporting period, development tests were initiated on the basic components of the engine assembly, as well as on materials, as follows:

Seven subscale ablative-chamber tests were conducted.

Tests were conducted on six subscale injectors in order to determine their performance capabilities.

Water-flow tests were conducted on one experimental valve that included seals of new design.

Samples of rubberized Refrasil resin were subjected to vacuum and high temperature tests. Results of these tests are being used to refine the design and to select suitable materials.

LAUNCH ESCAPE

Development Test Program

The following development-test program items were accomplished during this period.

Process studies of materials were continued.

Process specifications were prepared for the inert and live launch escape motors, the inert and live igniters, the batch-check motor, and a preliminary motor-process specification for the pitch-control motor.

Test bay modifications to accommodate the launch escape motor vertical thrust stand were completed by Lockheed.

A vacuum chamber for igniter and grain-port simulator tests was designed and fabricated.

Reliability assurance participated in the statistical planning of experiments and performed tests related to oxidizer studies and processibility studies.

Batch-check motor study was initiated and the casting of eight development motors was completed.

Methods of handling laboratory-test propellant samples were undertaken.

A laboratory study was made to evaluate three candidate adhesives for bonding insulation to the launch escape motor case.

Qualification-Reliability Testing

During this reporting period the revision to Lockheed's qualification-reliability test plan was not received. No qualification-reliability tests were conducted in this reporting period and no tests are scheduled in the next quarter.

TOWER JETTISON MOTOR

Development Test Program

The following development test program items were accomplished during this reporting period.

Four TE-381 pyrogens were successfully static tested.

Eighteen 5-inch ballistic test motors were successfully static tested.

Paint compatibility tests were conducted.

Qualification-Reliability Test Plan

The qualification-reliability test plan for the tower jettison motor was prepared by Thiokol. It adequately described the manner of data analysis for reliability assessment, but the document made no mention of methods to be employed in qualifying the rocket motor. As a result, the test plan is being revised to include this information.

Qualification-reliability tests on the tower jettison motor will commence in May 1963.

REACTION CONTROL

Developmental Testing

Developmental testing of the first 100-pound-thrust engine in a simulated altitude environment was initiated with no apparent combustion chamber degradation. Altitude tests were also conducted with a single doublet injector head to evaluate nozzle-expansion section length and to substantiate previous nozzle-length data. Solenoid-valve response tests conducted during the early part of this quarterly report period demonstrated satisfactory opening response. In addition, two endurance tests of 100,000 cycles each were conducted with two solenoid valve seat assemblies that showed less than allowable leakage. A number of materials studies and process studies were conducted in support of the development effort. These studies include:

Studies of forgings of high purity, sintered molybdenum for thrust chambers.

Evaluation of oxidation protective coatings for molybdenum.

Evaluation of service life of various types of molybdenum coatings.

Compatibility evaluations of propellants with the various system materials.

Qualification-Reliability Testing

As of this date, no qualification-reliability test plan has been submitted by Marquardt.

Qualification-reliability tests of the service module reaction control engines are scheduled to be initiated in March 1963.

HEAT SHIELD

Adhesive Materials

Definitive experiments for evaluating and comparing eleven adhesive materials for optimum bonding design of substrate and heat-shield materials were completed.

Nondestructive Acceptance Testing Techniques

The study of non-destructive test techniques for acceptance testing of production heat shield tiles is continuing. Applicability of the results of this test to reliability evaluation appears promising. The main concern is determining the following discrepancies within each heat shield panel: internal flaws, voids, density variations, moisture content, surface cracks, tensile strength, modules of elasticity, separation, specific heat variations, and bond quality.

Preliminary Radiographic Inspection Method

A preliminary test method for radiographic inspection of brazed honeycomb test panels having 2-inch thick cores has been developed. Avco and S&ID reliability agreed that Avco will supply failure data in a manner adaptable to S&ID's electronic data processing system.

EARTH LANDING

Parachute Development Tests

Three parachute development drops were conducted at El Centro during July to verify chute design as related to reefing diameter and rate of descent. Failures of the crown of the parachute canopy on two of the tests proved the need for additional reinforcement in this area. Two parachute drops were conducted during the month of August and five during September.

Other Test Efforts

Other tests in progress in the laboratory include:

Fabric structural test

Pull test on deployment bag bridle

Material environmental tests (nylon, dacron, HT-1, and cotton sateen)

Material elongation tests

STABILIZATION AND CONTROL

Qualification-Reliability Test Plan A62-751E2(1)

This qualification-reliability test plan was submitted for approval during the quarter. In the initial review, the proposed approach that was based only on the statistical method advocated by the advisory group in reliability of electronic equipment (AGREE) was considered inadequate. An exercise in cost reduction was carried on during the quarter in conjunction with a study concerning the application of a modification of the method originally proposed. The number of equivalent test systems was set at 15.

General Test Program Status

Only limited breadboard circuit development tests were initiated during this quarter. These include test activities on breadboard and parts applications and suitability tests.

Special Reliability Tests

Minneapolis-Honeywell initiated a program to qualify all materials proposed for use in the stabilization control system to the environmental requirements of outgassing, inflammability, and oxygen resistance. The company completed evaluation and certified as acceptable some 50 types of materials during the quarter. Test results are contained in the Minneapolis-Honeywell/S&ID monthly customer-engineering letter.

TELECOMMUNICATIONS

Collins Radio Company and S&ID reliability engineering expended considerable effort on development of a qualification-reliability test plan. The activation of this plan will demonstrate the apportioned reliability of the communications and data subsystem at the desired confidence level. A mission test profile has been established which will simulate, where practicable, the mission conditions for the communication system. The combined environments are being selected and the duration of exposure to each environment is being assigned. The statistical design of the tests has been focused upon the amount of accumulated test time for the 10 equivalent subsystems scheduled for the qualification-reliability test program. This quantity recently received NASA approval.

Melpar, Inc., submitted a qualification-reliability test outline which was disapproved by the S&ID reliability test group due to cost limitations. The reliability engineering group has provided redirection in the form of a revision of the procurement specification to enable Melpar to submit a revised cost proposal and a mutually acceptable qualification-reliability test plan in the next reporting period. The test plan will direct the test effort toward qualification of the R&D antennas and the power divider. Melpar will qualify three of each item by combined and sequential environmental testing, for a duration in each test environment equivalent to three missions. The end use (boilerplate) for the R&D items supplied by Melpar does not warrant an extensive reliability-demonstration program.

INSTRUMENTATION

Central Timing Equipment

A supplier of central timing equipment has not been selected; however, a preliminary qualification-reliability test plan has been written and included in the procurement specification, MC456-0006.

In-Flight Test System

A supplier of the in-flight test system has not been selected; however, a preliminary qualification-reliability test plan has been written and included in the proposed procurement specification, MC901-0063.

Special Purpose Electrical Connectors

A supplier of the special purpose electrical connectors has not been selected; however, a preliminary qualification-reliability test plan has been written and included in the procurement specification, MC414-0061.

GROUND SUPPORT EQUIPMENT

Reliability Test Activities

Reliability test activities during the third quarter of 1962 centered around reviewing and making comments on design, preliminary, model, and procurement specifications.

Test Plan Studies

Studies are being made that will define qualification-reliability test plans for various subcontractors as well as for in-house testing. A reliability demonstration program has been established that will use a 90-percent confidence level for mission-essential equipment and a 60-percent confidence level for mission-nonessential equipment. To the greatest extent possible, all testing performed within the scope of this demonstration program, will integrate the maximum applicable information and assure high-confidence reliability statements. The tests are to be based on a sequential test plan as delineated in MIL-A-26667A, but they will be truncated in the case of mission-nonessential equipment as a function of schedule commitments, or at the 60-percent confidence level, whichever comes first.

IV. DATA OPERATIONS

In support of contractual requirements, data-management personnel have participated in the development of data systems and in the acquisition of significant data.

PARAMETRIC DATA

Requirements are being defined for a data processing system to accumulate functional parameter data. This performance analysis and test histories (PATH) system will provide for computer processing of results from development, qualification-reliability, acceptance, and system tests. The data will be retained on magnetic tape for reference purposes and will be used to generate and prepare statistical reports for reliability analyses. In order to most effectively utilize the large volume of parametric data that will be generated, effort will be concentrated on providing systematic means for retention, monitoring, and retrieval. In addition, careful checking procedures will be employed to insure proper identification, accuracy, and validity of the obtained data. The basic system will be expanded to produce outputs for specific applications as requirements are defined.

A quality assurance operating procedure (QAOP) for test success and parametric data is presently being evaluated prior to implementation. This procedure defines responsibilities for the recording of parametric data for input to the PATH system.

SELECTED DATA REPORTING

Preliminary studies are in progress to determine the feasibility of combining selected data outputs from the various data systems being developed. The primary purpose is to produce composite reports of pertinent and related data. One such report under investigation is a listing of individual parts, components, and subsystems for the design configuration and the as-built configuration. Included in the report will be operating time logged against the items, functional test report numbers, and the qualification status. This particular report would entail the merging of selected outputs from the seven individual systems.

[redacted]

HISTORICAL DATA

A plan of action for the acquisition, recording, storage, and retrieval of equipment-and-part historical data having reliability significance is being finalized. The prime objective of the plan is to provide a method of cross-referencing data generated on various end items, systems, equipment, or parts, and, in addition, to provide a functional history for use in design selection and improvements of material and components. The type of documentation to be referenced in these records are

Associated specifications and technical orders

Functional and performance studies

Test reports by type and number

Statistical data

Problem report summaries

Application by project and system

SUBCONTRACTORS' AND ASSOCIATE CONTRACTORS' DATA REPORTING

A summary of data formats and data reporting systems for subcontractors and associate contractors is in progress. Effort is directed towards the development of a compatible reporting system and format which will be applicable to all subcontractors and associate contractors submitting reports to S&ID.

INTERSERVICE DATA EXCHANGE PROGRAM

During this report period, S&ID actively participated in the interservice data exchange program (IDEP). Since July, a total of 163 requested IDEP reports have been reproduced and distributed to various Apollo engineering groups. These reports have covered such components as capacitors, connectors, resistors, diodes, and transistors. Edit routines have been developed which will identify or delete incorrect information submitted to this program. In view of the significance of this program, appropriate plans for publicizing IDEP within S&ID have been coordinated with the division public relations group.

V. TRAINING AND EDUCATION

Effort continued in the area of education and training with the following activities conducted during the quarter as shown in Table 30.

Table 30. Education and Training Activity

Subject	Period	Number of Classes Given	Average Attendance	Total Attendance
Fundamentals of Reliability Mathematics	July	5	31.2	156
	Aug	5	26	130
	Sept	5	14	70
	Total	15	23.7	356
Computer Methods of Design Analysis	Aug	2	29.5	59
	Sept	4	25	100
	Total	6	26.5	159
Minuteman High-Reliability Parts	Aug	1	9	9
	Sept	2	9.5	19
	Total	3	9.3	28
High-Reliability Parts Symposium	July	1	125	125

In September, a letter was sent to Minneapolis-Honeywell Regulator Company in response to a request for course outlines and lecture notes of reliability courses. This letter contained only course outlines and representative sample lecture notes; however, complete lecture notes on the Fundamentals of Reliability Mathematics will be forwarded shortly. Lecture notes on Design Analysis Techniques will be forwarded about 1 December 1962.

VI. COMPONENT TECHNOLOGY

STUDIES

Evaluation and investigation of components scheduled for application in the Apollo spacecraft continued during the quarter. Several reports and letters were completed and issued, including the following.

CIRCUIT BREAKERS

This paper reports an evaluation of circuit breakers manufactured by the Klixon Company and by the Mechanical Products Company. Klixon D6761 and Mechanical Products 2900 are not recommended for Apollo usage. Klixon D7274-1, D7271-1 and D7276, and Mechanical Products 1500 and 1526 are recommended for use, provided the manufacturer's application limitations are followed.

RESISTORS

This reports on a study of resistors which included carbon composition, carbon film, tin oxide, ceramic encased, and glass encased types. Failure rates, radiation levels, application information, electrical, and physical characteristics were compared for each of the above types.

In addition, a draft of a proposed product specification, Defined Reliability for Resistors (fixed, wirewound, power type) was completed. This document, when used to support applicable SCD's, will provide the required controls for purchasing of parts that have demonstrated required levels of reliability.

ROTARY SWITCHES

A study of rotary switches manufactured by Janco, Cinema Engineering and Daven Company is reported. Since only the Janco switch utilized closed-type construction, it was rated highest of the three. However, it is strongly recommended that the Janco switch be upgraded by hermetic sealing and that only hermetically sealed switches be used on the Apollo.

RADIATION AND VACUUM EFFECTS

This presents a detailed investigation of high-energy radiation and hard-vacuum effects upon electronic components. Damage threshholds and damage modes are indicated for electron tubes, gas tubes, resistors, capacitors, transformers, connectors, semiconductors, and transistors.

TEMPERATURE, ACOUSTIC, AND RANDOM VIBRATION EFFECTS

This reports an investigation of the effects of temperature, acoustic and random vibration upon transformers, transistors, resistors, diodes, and capacitors.

SOLDERING, WELDING, WIREWRAPPING, AND WIRE TERMINATING METHODS

Soldering, welding, wirewrapping, and wire terminating methods are reported. Reports indicate a mean time between failures of 5, 000, 000 hours for soldered connections. Optimistic reports exist on wirewrap methods; however, use of stranded wire as normally required in spacecraft would obviate most advantages.

FAILURE RATES OF SELECTED LAMPS AND COMPONENTS

This discusses predicted failure rates for selected incandescent lamps, quartz lamps, fluorescent lamps, lamp ballasts, variable transformers, and potentiometers.

CO-AXIAL SWITCHES

A study of Transco 2.3 kmc co-axial switches is reported. Predicted failure rates are 0.7 percent per 1000 hours for Type M (manual operation) and 0.09 percent per 1000 hours for Type Y (solenoid transfer, SPDT) when operated at a rate of one cycle per minute with a crosstalk of approximately 50 decibels.

WIREWOUND-RESISTOR DRAWING

This is a review of SCD ME-443-0044 (resistor, wirewound). It was not approved for use by the component technology group. Minimum requirements to upgrade the document were developed.

AC AND DC MOTORS

This reports an evaluation of AC and DC motors proposed for use in driving the hydrogen and water separator. Brushless AC motors are recommended over DC motors because utilization of the AC type would eliminate or alleviate the following prominent failure modes.

a. Brush wear

b. Brush out-gassing

c. Lubrication contamination (due to items a and b)

d. Catastrophic bearing failure (due to item c)

It should be noted that problem areas still exist, including the out-gassing of insulation materials that results in loss of circuit isolation and the contamination of lubrication.

RADIATION LEVELS

The radiation levels anticipated for parts located immediately within the outer hull of the Apollo spacecraft were outlined as a basis for radiation criteria for Apollo parts specifications.

TRAVELING WAVE TUBES

Traveling wave tubes (2.3-kmc to 20-watt output) manufactured by Hughes Aircraft Company and by Watkins-Johnson were investigated. It was found that the tube proposed for Apollo usage has never been produced; however, both manufacturers were conducting tests on items that were quite similar in both electrical and mechanical aspects.

At the time of the investigation, the following test information was available.

Hughes part 349N had been operated 44,324 hours without failure (at 40 C above normal operating temperature).

The Watkins-Johnson part had been operated 50,000 hours with one failure (at normal temperature).

ADDITIONAL EFFORTS FOR QUARTER

Effort is also continuing in the following areas:

Completion of the first edition of a preferred parts list

Investigation of methods and procedures for the transportation, handling, storage, and assembly techniques that will be proposed for use with high-reliability parts

Determination of failure rates and availability of selected Leach relays

Investigation of parts manufactured by three suppliers in order to evaluate the feasibility of replacing a computer diode (FS760) with a high-reliability, general purpose computer diode (479-0468-427M)

Failure-rate information and statistical-parameter-behavior information at various temperature conditions

Determination of failure rates for three types of G. E. quartz lamps

Investigation of fluid fittings is under way. Proposed test plans have been documented and 22 prospective suppliers have been contacted for required information. This information is currently being evaluated in order to most effectively utilize test funds

Evaluation of Resdel Engineering Corporation's cavity amplifiers

Development of test plans and screening techniques for various high-reliability electronic parts

Continuation of radiation and hard vacuum studies. Test plans and testing facilities are being investigated

Review and establishment of quality assurance requirements in part-control documentation

VII. SUPPLIER SURVEYS

Pre-award surveys constituted the major effort during the past quarter, and these are summarized in Table 31. During the next quarter, approximately thirty-five additional pre-award surveys will be conducted, primarily in the areas of fuel tanks, the central timing unit, and the ground cooling cart. Also, six resurveys are scheduled for potential suppliers who have either modified their reliability controls or instituted policies and procedures to establish approved systems.

Post-award surveys are scheduled to commence during the next quarter; two are planned.

A definitive procedure for supplier surveys was generated and is now in use for all surveys. This procedure, "Supplier Survey Handbook for Reliability Engineering," includes methods for preparing surveys, procedures for conducting surveys, and a detailed questionnaire for supplier evaluation. Areas covered are management, planning, technical evaluation, test capabilities, and documentation systems.

Summarization of all surveys conducted through September, a total of 71, was completed and copies of the summary were distributed to various departments for their use. Included in this summary is the supplier disposition and description of deficiencies observed. This summary will be maintained and updated periodically to include post-award survey data as it is obtained.

[redacted]

Table 31. Supplier Surveys

Equipment	Name of Supplier	Location
Battery charger	Arnold Magnetics	Los Angeles, California
	Delco Radio	Kokomo, Indiana
	Electro Development	Seattle, Washington
	Hughes Electronics	Los Angeles, California
	Magnetics Research	Hawthorne, California
	Valor Instruments	Gardena, California
Propellant utilization system	Avain	Woodside, New York
	Simmons Precision Prod.	Vergennes, Vermont
	Whittaker Controls	Chatsworth, California
	Whittaker Controls	Van Nuys, California
Data reduction	Daystrom, Inc.	Archbald, Pennsylvania
	Molecular Research	West Palm Beach, Florida
	System Engineering Labs	Fort Lauderdale, Florida

[redacted]

[redacted]

Table 31. Supplier Surveys (Cont)

Equipment	Name of Supplier	Location
Static inverter	Hamilton Standard	Broadbrook, Connecticut
	ITT Industrial Products	San Fernando, California
	Varo	Garland, Texas
	Westinghouse	Lima, Ohio
Telemetry station	Arnoux	Culver City, California
Telecommunications	Hallicrafters	Santa Ana, California
Miscellaneous	Bay State Electronics	Southbridge, Massachusetts
	Sperry-Utah	Salt Lake City, Utah

[redacted]

[redacted]

VIII. TRIPS AND MEETINGS

MIT-S&ID RELIABILITY MEETING

On 5 and 6 September 1962, a meeting was held at the Massachusetts Institute of Technology (MIT) to discuss the reliability of the guidance and navigation equipment. The discussion included a review of the alternate modes of operation available through use of stabilization and control systems equipment and communications and data equipment, and the navigational accuracy of these modes. MIT presented detailed reliability analyses of some of their equipment and conducted a short discussion of their reliability program.

S&ID began the meeting by presenting the briefing which was presented to NASA at Houston on 17 and 18 July 1962. This presentation included:

Reliability logic diagrams, including available alternate modes for the navigation and control functions.

Estimated subsystem and system reliabilities based upon high-reliability and state-of-the-art parts.

Estimated accuracies for these modes.

Relation of recovery forces to touchdown-area dispersion.

MIT presented the results of a reliability analysis of the Apollo guidance computer (AGC) and the power servo-assembly (PSA). These analyses were based upon Radio Corporation of America failure rates and upon failure rates extrapolated from Mark II Polaris data. Based on the RCA failure rates, the estimated mean time between failures (MTBF) for the computer is 204 hours; based on Polaris data it is 632 hours. Using the Polaris failure rates, MIT estimated that the computer would meet its reliability requirements if seven of the twenty-four modules were carried as on-board spares. This is based on the condition that the computer operates for 14.6 hours during the mission, and that no failures would occur when it was not operating. The figure of 14.6 hours results from the MIT estimate of time that the computer would be required to operate during the translunar phase only; the return phase was not considered for reliability calculations.

[redacted]

[redacted]

The estimated MTBF's for the power servo-assembly were 485 hours using RCA data, and 1850 hours using Polaris data. Basing its calculations on a running time of 5-1/2 hours (translunar only), MIT stated that the power servo-assembly could meet its requirements with on-board spares. MIT stated that they could not meet their reliability requirement for the electronics without the use of on-board maintenance.

Based on Polaris data, MIT felt that the inertial measurement unit reliability requirements could be met without on-board maintenance. This assumed an MTBF of 574 hours for the Mark I system measured on-board submarines, and an estimated MTBF of 2240 hours for the Mark II version. The apportioned value was 4000 hours, based on the inertial measurement unit being run for 5-1/2 hours during the translunar phase.

Since this analysis was originally made, it appears that the decision to turn off the inertial elements in the inertial measurement unit will be reversed, and that the wheels and bearings will run continuously. Since these elements are considered the greatest potential problem area, the required MTBF will undoubtedly be increased.

MIT presented their apportioned values of reliability as shown in Table 32.

Table 32. Massachusetts Institute of Technology Apportionments of Reliability

Subassembly	Operating Time (hours)	Spare Sticks	Mean Time Between Failures (hours)	Reliability
Display and control equipment	14.6	1	42,700	0.999658
Sextant	14	0	7,800	0.998200
Inertial measurement unit	5.5	0	3,060	0.998200
Apollo guidance computer	14.6	10	8,550	0.998290
Power and servo assembly	5.5	11	17,100	0.999678
Final approach equipment	5.5	0	17,100	0.999971

[redacted]

During further discussions, MIT stated that they planned no parts development program to achieve their reliability levels. They felt that the reliability levels could be achieved by the use of on-board spares. However, a certain number of parts will be developed to reduce the size and increase the performance of the system. Additional development work is being done on micrologic circuits. Concern was expressed by S&ID regarding the difficulty of developing a basic design and adequate process controls to achieve the required level of reliability on a newly developed part with an extremely limited production. MIT stated that there is a parallel design with conventional parts that might be used if the development of new parts were not successful. Although MIT anticipated no parts improvement program, they agreed to participate in the joint Apollo committee presently planned by S&ID. Description of the MIT program content and requirements will not be available until the first design freeze.

ADDITIONAL TRIPS AND MEETINGS

A summary of other trips and meetings is given in Table 33.

~~CONFIDENTIAL~~

Table 33. Trips and Meetings

Discussion	Participation	Date
Cost-Proposal Analysis	Collins S&ID	2 to 6 July
Monthly Coordination	Avco S&ID	9 July
Data Input for Monte Carlo Reliability Model	NAA/LAD S&ID	12 July
NAA Reliability Studies	NASA S&ID	19 July
Apollo High-Reliability Parts Symposium	NASA/NAA AiResearch Collins Radio Minneapolis-Honeywell Northrup/Ventura Pratt & Whitney	19 July
Statement-of-Work Review	Collins Radio S&ID	30 July
Off-Limit Reliability Tests For Components, and Mission-Simulation Requirements For Qualification-Reliability Tests	AiResearch S&ID	30 July
Review of Lockheed Propulsion Company's Reliability Program Plan and Qualification-Reliability Test Plan	Lockheed Propulsion S&ID	1 August
Research and Development Telemetry Antenna	Transco S&ID	3 August
Reliability Program, Support Facilities, and Qualification-Reliability Testing	Collins Radio S&ID	6 to 10 August

~~CONFIDENTIAL~~

[redacted]

Table 33. Trips and Meetings (Cont.)

Discussion	Participation	Date
Apollo Reliability Program Presentation for Dr. Golovin, NASA	NASA S&ID	8 August
Oscilloscope for Use in the In-Flight Test System	Tektronix S&ID	9 August
Stabilization Control System Design Review	Minneapolis-Honeywell	13 August
Analysis of Stabilization and Control Cost Proposal	Minneapolis-Honeywell S&ID	20 August
Reliability Testing and Cost Justification For Contract Definition	Pratt & Whitney S&ID	21 August
Compatibility of Data Handling	Northrup/Ventura S&ID	22 August
Qualification-Reliability Testing	Northrup/Ventura S&ID	23 August
Effects of Increased Packaging Density	Collins S&ID	24 August
Component Relocation, In-Flight Instrumentation, and Failure Effects on System Reliability	AiResearch S&ID	27 August
Research and Development Beacon Antenna	Melpar S&ID	29 August
Quarterly Briefing by Minneapolis-Honeywell Management	Minneapolis-Honeywell S&ID	29 August
Cost Reduction	Avco S&ID	3 September

Table 33. Trips and Meetings (Cont.)

Discussion	Participation	Date
Guidance and Navigation Equipment Reliability Program and Test Planning	NASA S&ID	5 to 6 September
Reaction Control System Proposal Cost Reduction	Marquardt S&ID	5 to 7 September
Cost Reduction	Collins S&ID	5 to 6 September
Cost Reduction	Minneapolis-Honeywell S&ID	6 to 7 September
Monthly Coordination	Collins Radio S&ID	7 September
Micro-Module Packaging Briefing by RCA	RCA S&ID	7 September
Failure-Mode Analysis Logic Block Diagrams	Minneapolis-Honeywell S&ID	13 September
Traceability Requirements and Reliability Confidence Level	Collins Radio S&ID	18 September
Reliability Training Material	Minneapolis-Honeywell S&ID	19 September
Stabilization Control System Design Review	Minneapolis-Honeywell S&ID	21 September
Monthly Coordination	AiResearch S&ID	24 September
Reliability Program Plan, SID 62-203, and Qualification-Reliability Test Plan SID 62-204	NASA/MSC S&ID	27 to 28 September

IX. PLANNED ACTIVITIES

SPACECRAFT SUBSYSTEMS

RELIABILITY APPORTIONMENT FOR ELECTRONIC SUBSYSTEMS

Subsystem reliability apportionments for all electronics subsystems, based on minimum part improvement efforts and overall mission success requirements, are being formulated. Equations synthesizing system-failure probabilities are being programmed for the IBM 7090 computer to calculate system-failure events due to individual-part failures.

Studies of the electronic subsystems will be conducted to ascertain the most efficient methods of attaining the apportioned equipment reliability values, including the following trade-offs:

Parts improvement

Redundancy

Spares

Maintenance concepts

Overall weight considerations

Parameter-variation analyses will be performed in greater detail as electronic-circuit designs become available. Failure-mode and contingency analysis will be conducted to determine effects on equipment, subsystems, and overall mission success. Reliability engineering will take part in design reviews as subsystems equipment becomes sufficiently defined.

ENVIRONMENTAL CONTROL SUBSYSTEM

Revision of environmental control system network reliability logic networks, associated mathematical models, and failure-mode and effects analysis, and reapportionment of component and subsystem reliability goals is planned for the next quarter.

~~CONFIDENTIAL~~

SUPERCRITICAL GAS STORAGE

The system-procurement specification for supercritical gas storage will be revised to delineate firm reliability design requirements to the subcontractor. Because of design changes, a re-evaluation of the system reliability will be performed; a review of the failure-mode analysis will also be performed.

[redacted]

PROGRAM IMPLEMENTATION

CREW-SAFETY AND MISSION-SUCCESS CRITERIA

The mission-success and crew-safety criteria are now being analyzed using various mathematical relationships. Numerical relations between mission success, crew safety, and probability of safe abort of various mission phases are being formulated. Abort criteria based on the results of this study are being developed.

SUBCONTRACTOR DATA REPORTING

A summary of data formats and data reporting systems is being prepared. Present effort is directed toward developing a reporting system and format that will be applicable to all Apollo subcontractors.

QUALIFICATION-RELIABILITY TESTING

A task force is being assembled to review the spacecraft system-test program. Information resulting from this review will be employed to define the detailed requirements for qualification and reliability demonstration of critical functions at the systems level. This activity is aimed at assuring a proper evaluation of all systems prior to the first manned flight.

STATISTICAL ANALYSIS

A mathematical model to demonstrate reliability at a high confidence level using small sample sizes is being developed. The model involves the application of Chebzshev's Inequality and requires the effective integration of design, quality control, and reliability functions. Results obtained by this method compare favorably with those achieved by the presently employed "non-central t" distribution method, having been shown to be within three percent. The model can be used for reliability assessments of selected parameters during the qualification-reliability tests.

~~CONFIDENTIAL~~

Table A-1. Procurement Specification Contributions

Specification Number	Title
MC 284-0001	Valve, Solenoid (N. O.)
MC 284-0018	Valve, Solenoid (N. O.)
MC 284-0020	Regulator, Pressure
MC 284-0022	Regulator, Pressure
MC 284-0019	Valve, Squib
MC 284-0024	Valve, Check
MC 284-0025	Valve, Check
MC 284-0026	Valve, Relief
MC 284-0027	Valve, Relief
MC 273-0009	Disconnect, Fill
MC 273-0010	Disconnect, Fill
MC 273-0011	Disconnect, Vent
MC 273-0012	Disconnect, Vent
MC 273-0018	Disconnect, Fill
MC 273-0019	Disconnect, Fill
MC 273-0020	Disconnect, Fill
MC 273-0021	Disconnect, Fill
MC 273-0022	Disconnect, Vent
MC 273-0024	Disconnect, Vent
MC 251-0004	Diaphragm, Burst
MC 251-0005	Diaphragm, Burst
MC 284-0013	Valve, Solenoid (N. O.)
MC 284-0045	Valve, Solenoid (N. O.)
MC 901-005	Cryogenic Gas Storage System
MC 414-0015	Fuel Cell Electrical Powerplant
MC 901-0031	Prototype Stabilization Control System Bench Maintenance Equipment

~~CONFIDENTIAL~~

[redacted]

Table A-1. Procurement Specification Contributions (Cont)

Specification Number	Title
MC 901-0033	Prototype Stabilization Control System Bench Maintenance Equipment
MC 999-0019	Cable Assemblies, Special Purpose, Electrical, Apollo GSE
C14-031	On-Board Recorder Checkout Unit
MC 901-0041	Stabilization Control System Auxiliary GSE
MC 901-0057	Fuel Cell Powerplant Test Stand
MC 456-0006	Central Timing Equipment
MC 449-0005	Pressure Transducer
MC 901-0063	In-Flight Test System
MC 481-0001	Research and Development Telemetry Antenna
MC 481-0003	Research and Development Beacon Antenna
MC 495-0001	Inverter, Power, Static, 115-200 volt
MC 461-0003	Battery, Spacecraft, Storage, Zinc-Silver Oxide
MC 461-0002	Charger, Battery, Zinc-Silver Oxide
MC 901-0024	Vacuum Cleaner
MC 901-0025	Waste Management Control Unit
MC 901-0027	Bacteria Control Unit
MC 901-0029	Urine Disposal Lock
MC 901-0050	Air Flow Check Valve
MC 901-0028	Blower
MC 901-0068	Back-up Valve
MC 453-0005	Cartridges, Electrically Initiated
MC 453-0006	Flexible Linear Charges
MC 481-0006	Command Module Radome

[redacted]

~~CONFIDENTIAL~~

Table A-1. Procurement Specification Contributions (Cont)

Specification Number	Title
MC 282-0013	Pressurant and Propellant Tanks
MC 901-0032	Boilerplate Stabilization and Control System

~~CONFIDENTIAL~~

Table A-2. Subcontractor Documents Reviewed

Source	Report No.	Title
Aerojet-General Corporation	AGC-10141	Service Module Rocket Engine Specification
	3865-1-1	Monthly Progress Report
	3865-1-2	Monthly Progress Report
	3865-1-3	Monthly Progress Report
	3865-2-1	Monthly Weight and Balance Report
	3865-2-2	Monthly Weight and Balance Report
	3865-2-4	Monthly Weight and Balance Report
	3865-3	Program Plan
	3865-6	Reliability Program Plan
	3865-9	Quality Control Plan
	3865-9A	Quality Control Plan
	3865-11	Reliability Test Plan
	3865-11A	Reliability Test Plan
	3865-13 Amend I	Test Plan
	3865-14-2	Quarterly Progress Report
	3865-30-1	Quarterly Reliability Status Report
	3865-34	Inspection, Measuring, and Test Equipment Procedures
	3865-35	End-Item Test Plan
	3865-507	Performance Degradation Caused by a Loss of 50 BTU per Second from the Rocket Chamber
	3865-508	Effect of Gas Injection Upon Engine Operation
AiResearch Manufacturing Corporation	SS-1000-R Rev 4	System Specification, Schematic Diagram
	SS-1002-R Rev 2	GSE Performance and Interface
	SS-1003-R Rev 1	Reliability Program Plan
	SS-1005-R Rev 2	Facilities Plan
	SS-1010-R Rev 1	Quality Control Plan
	SS-1010-R Rev 2	Quality Control Plan
	SS-1012-R Rev 1	End-Item Test Plan
	SS-1013-R	Monthly Progress Report
	SS-1013-R(4)	Progress Report

~~CONFIDENTIAL~~

Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
AiResearch Manufacturing Corporation	SS-1013-R(5)	Progress Report
	SS-1014-R	Design Criteria Specification
	SS-1017-R Rev 4	Monthly Weight and Balance Report
	SS-1017-R Rev 5	Monthly Weight and Balance Report
	SS-1018-R	Pressure Suit Test Program Report
	SS-1019-R(2)	Progress Report
	SS-1020-R Rev 1	Program Plan
	SS-1027-R	Drawing List
	SS-1027-R Rev 1	Drawing List
	SS-1033-R	Heat Transport Fluid Optimization Study
	SS-1035-R	Quarterly Reliability Status Report
	SS-1042-R(2)	PERT Biweekly Report
	SS-1042-R(3)	PERT Biweekly Report
	SS-1042-R(4)	PERT Biweekly Report
	SS-1042-R(5)	PERT Biweekly Report
	SS-1042-R(6)	PERT Biweekly Report
	SS-1042-R(7)	PERT Biweekly Report
	SS-811100	Equipment Specification, Solids Trap
	SS-812100	Equipment Specification, Heat Exchanger
	SS-820902	Equipment Specification Cabin Temperature Control System
	SS-826000	Equipment Specification, Motor-Driven Centrifugal Compressor
	SS-826010	Equipment Specification Motor-Driven Vaneaxial Fan
	SS-827030	Equipment Specification, Check Valve
	SS-827040	Equipment Specification Quick Disconnect Coupling
	SS-827050	Equipment Specification, Shut-Off Valve
	SS-827060	Equipment Specification Quick Disconnect Coupling

~~CONFIDENTIAL~~

Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
AiResearch Manufacturing Corporation	SS-827220	Equipment Specification, Solenoid Valve
	SS-827270	Equipment Specification, Check Valve
	SS-827310	Equipment Specification, Metering Valve
	SS-827360	Equipment Specification, Check Valve
	SS-827410	Equipment Specification, Plug Valve
	SS-844000	Equipment Specification, Low Pressure Gaseous Test Stand
	SS-844100	Equipment Specification GSE High Pressure Gaseous Test Stand
	SS-844200	Equipment Specification, Liquid Test Stand
	SS-844300	Equipment Specification, Electrical Test Stand
	SS-844700	Equipment Specification GSE Glycol Service Unit
Avco Corporation	RAD-SR-62-99 Rev 1	Qualification-Reliability Test Plan
	RAD-SR-62-99 Part I	Reliability Program Plan
	RAD-SR-62-99 Part IIA	Qualification-Reliability Test Plan
	RAD-SR-62-99 Part IIB	Reliability Test Plan
	RAD-SR-62-100	Heat Shield Phase I Biweekly Progress Report
	RAD-SR-62-102	Manufacturing Plan
	RAD-SR-62-102 Rev 1	Manufacturing Plan
	RAD-SR-62-106	Inspection, Measuring, and Test Equipment Procedures
	RAD-SR-62-110	End-Item Test Plan
	RAD-SR-62-112	Preliminary Quality Control Plan

Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
Avco Corporation	RAD-SR-62-112 Rev 1	Quality Control Plan
	RAD-SR-62-113 Rev 1	Test Plan
	RAD-SR-62-115	Program Plan
	RAD-SR-62-115 Rev 1	Program Plan
	RAD-SR-62-117	Heat Shield Phase I Biweekly Progress Report
	RAD-SR-62-130	Heat Shield Phase I Biweekly Progress Report
	RAD-SR-62-187	Qualification Status List
	RAD-SR-62-188	Monthly Progress Report
Beech Aircraft Corporation	13703	Program Plan
	13705	Test Plan
	13707	Reliability Plan
	13709	Quality Control Plan
	13711	End-Item Test Plan
Collins Radio Company	AR-101-4	Monthly Progress Report
	AR-101-5	Monthly Progress Report
	AR-101-6	Monthly Progress Report
	AR-104-3	Design Criteria Specification
	AR-105-3	GSE Performance and Interface
	AR-111-2	Program Plan
	AR-113-3	Qualification-Reliability Test Plan
	AR-118-2	Quality Control Plan
	AR-118-2 Rev	Quality Control Plan
	512-2284-00	Preliminary Equipment Specification, R&D VHF Diplexer
	512-2284-00	Preliminary Equipment Specification, R&D Multiplexer
	AR-120-2	Quarterly Progress Report
	AR-120-3	Quarterly Progress Report
	AR-125-2	Equipment Specification, VHF Antenna Switch
	AR-128-2	Equipment Specification, C-Band Transponder Equipment

[redacted]

Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
Collins Radio Company	AR-130-3	Equipment Specification, DSIF Transponder
	AR-131-2	Equipment Specification, Telemetry Equipment
	AR-131-3	Equipment Specification, Telemetry Equipment
	AR-136-2	Equipment Specification, Data Storage Equipment
	AR-137-2	Equipment Specification, VHF/2KMC Omni Antenna
	AR-146-2	Equipment Specification, Aide Units
	AR-149-2	Equipment Specification, Systems Test
	AR-157-2	Equipment Specification, Bench Maintenance Equipment
	AR-166-1	Special Sampling Plan
Lockheed Propulsion Company	588-M-5-R-1	Equipment Specification, Launch Escape Motor
	588-M-8	Qualification-Reliability Test Plan
	588-M-9	Manufacturing Plan
	588-M-10	Drawing Test
	588-M-11	Final Quality Control Plan
	588-M-13	End-Item Acceptance Test Plan
	588-M-14	Drawing List (Revision)
	588-M-15	Drawing List (Revision)
	588-M-19	Inspection and Test Procedures
	588-M-21	Inspection, Measuring, and Test Equipment Procedures
	588-M-22	Monthly Quality Report
	588-M-23	Drawing List (Revision)
	588-M-24	Qualification Status List
	588-M-25	Drawing List
	588-M-26	Monthly Quality Report
	588-M-27	Drawing List (Revision)
	588-P-2	Monthly Progress Report
	588-P-3	Monthly Progress Report
	588-P-4	Monthly Progress Report
	588-Q-1	Quarterly Progress Report
	588-Q-2	Quarterly Progress Report

~~CONFIDENTIAL~~

Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
Marquardt Corporation	ROIM	Reliability Operations Instructions Manual
	A-1001	Inspection, Measuring, and Test Equipment Procedures
	A-1001-1	Inspection, Measuring, and Test Equipment Procedures
	A-1002	Reliability Program Plan Part I
	A-1003	Facilities Plan
	A-1004	Program Plan
	A-1005 A	Manufacturing Plan
	A-1005 B	Manufacturing Plan
	A-1006	Quality Control Plan
	A-1006 A	Quality Control Plan
	A-1008 A	End-Item Test Plan
	A-1009	Hardware List
	A-1011-1	Monthly Progress Report
	A-1011-2	Monthly Progress Report
	A-1011-3	Monthly Progress Report
	A-1015-1	Drawing List
	A-1015-4	Drawing List
	A-1015-5	Drawing List
	A-1015-6	Drawing List
	A-1020-2	Monthly Quality Report
	A-1026	Quarterly Progress Report
Melpar Incorporated	1004. 03	Factory Test Plan, R&D Beacon Antenna Reliability Program Plan
Minneapolis-Honeywell Regulator Company	A62-750A2(1)	Model Specification, Boilerplate Stabilization and Control System
	A62-750A3(1)	Model Specification, Prototype Stabilization and Control System
	A62-750A4(1)	Model Component Specification, Manual Controls
	A62-750A13(1)	Model Specification, Display Subsystem
	A62-750B2(1)	Model Specification, Bench Maintenance Equipment and Spacecraft Check-Out Group

[redacted]

Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
Mineapolis-Honeywell Regulator Company	A62-750B4(1)	Model Specification, Prototype Stabilization and Control System, Bench Maintenance Equipment
	A62-750B5(1)	Model Specification, Prototype Spacecraft System Check-Out Group
	A62-750H9(1)	Criteria Specification, Stabilization and Control System Manual Controls
	A62-751 C(1)	Test Plan
	A62-751 D	Manufacturing Plan
	A62-751 E1(1)	Reliability Program Plan
	A62-751 E1(2)	Reliability Program Plan
	A62-751 E2(1)	Qualification-Reliability Test Plan
	A62-751 F(2)	Maintenance Plan
	A62-751 G(2)	Support Plan
	A62-751 H1(1)	End-Item Acceptance Test Plan, Boilerplate Launch Escape Stabilization and Control
	A62-752 C(4)	Monthly Progress Report
	A62-752 C(6)	Monthly Progress Report
	A62-752 C(7)	Monthly Progress Report
	A62-756 A(2)	Quarterly Reliability Status Report
	A62-760 A7(1)	Human Factors Considerations for Manual Controls
	A62-760 A8(1)	Failure Indication Study, Stabilization and Control System
	A62-760B3.1(1)	Reaction Jet Emergency and Manual Control Study
	A62-760B13.1(2)	On-Board Monitor, Conceptual Study
	A62-760B36.1(1)	Initial Failure Analysis, Stabilization and Control System
	A62-768 B(3)	Quality Control Plan
	A62-768 D(2)	Monthly Quality Report

[redacted]

[redacted]

Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
Minneapolis-Honeywell Regulator Company	A62-777 A1(1)	Reaction Jet Test Stand, Console and Building, Detailed Description
	A62-777 A1(2)	Reaction Jet Test Stand, Console and Building, Detailed Description
	A62-760A4(1)	Apollo Mid-Course Stabilization and Control Study
	MHA 62-760AY	Apollo Mid-Course Stabilization and Control Study
	A62-777 A 2(1)	Reaction Jet Test Stand and Console Test Plan
	A62-777 A 2(2)	Reaction Jet Test Stand and Console Test Plan
	A62 777 A 3(1)	Dynamic Flight Simulator, Detailed Description
	A62 777 A 3(2)	Dynamic Flight Simulator, Detailed Description
	A62-777 A 4(1)	Dynamic Flight Simulator Test Plan
	A62-777 A 4(2)	Dynamic Flight Simulator Test Plan
	A62-777 A 5(1)	Attitude Control Evaluator and Buildings, Detailed Description
	A62-777 A 5(2)	Attitude Control Evaluator and Buildings, Detailed Description
	A62-777 A 6(1)	Attitude Control Evaluator Test Plan
	A62-777 A 6(2)	Attitude Control Evaluator Test Plan
	A62-777 A 7(1)	Continuous Control Evaluator, Detailed Description
	A62-777 A 7(2)	Continuous Control Evaluator, Detailed Description
	A62-777 A 8(1)	Continuous Control Evaluator, Test Plan
	A62-777 A 8(2)	Continuous Control Evaluator, Test Plan
	A62-777 B 1(1)	Technical Description, Control Amplifier Test Sets

~~CONFIDENTIAL~~

Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
Minneapolis-Honeywell Regulator Companry	A62-777 B 2(1)	Technical Description Guidance and Navigation Display and Controls
Northrop/ Ventura	NVC/62-1305-734	End-Item Test Plan, Design Criteria Specification
	PTM-487	Test Equipment Presentation
	PTM-489	Monthly Weight and Balance Report
	62-408	Monthly Progress Report Drawing List
	2187/734	Quarterly Reliability Status Report
	2520	Design Analysis, Earth Landing System
	2523 B	Test Plan
	2523 B Amend B	Test Plan
	2524 A	Manufacturing Plan
	2526	Reliability Demonstration Plan
	2536	Structural Fabric Test Plan
	59301	Equipment Specification, Switch Inertia
	59302	Equipment Specification, Baroswitch
	59305	Equipment Specification Switch, Time Delay
	59305 Rev	Equipment Specification, Switch, Time Delay
	59311	Equipment Specification, Cutter, Mechanically Initiated, Reefing Line
	59314	Equipment Specification, Relay, Non-Latching
	59315	Equipment Specification, Relay, Latching
	59331	Protective Finishes and Markings, Earth Landing System

[redacted]

Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
Pratt and Whitney Aircraft	PWA-4-5	Monthly Progress Report
	PWA-4-6	Monthly Progress Report
	PWA-6-3	Monthly Weight and Balance Report
	PWA-21-1	Hardware List
	PWA-21-2	Hardware List
	PWA-24-4	Drawing List
	PWA-24-5	Drawing List
	PWA-24-6	Drawing List
	PWA-2054	Test Plan
	PWA-2055	Reliability Program Plan
	PWA-2055 Rev	Reliability Program Plan
	PWA-2056	Manufacturing Plan
	PWA-2057	Reliability Test Plan
	PWA-2059	Quality Control Plan
	PWA-2059 Rev	Quality Control Plan
	PWA-2079 Rev A	End-Item Test Plan
	PWA-2084	Quarterly Progress Report
	PWA-6342 C	Specification, Shipping Container, Fuel Cell Powerplant
	PWA-PS-356 C	Purchase Specification
	PWA-PS-666	Purchase Specification
Thiokol	A-002	System Specification
	A-004 A	Test Plan
	A-005 A	Manufacturing Plan
	A-009	Preliminary Quality and Functional Acceptance Test Plan
	A-009 A	End-Item Test Plan
	A-012	Skewed Nozzle - Effect on Performance
	A-013	Part II Qualification-Reliability Test Plan
	A-015	Qualification Status Report
	A-201	Monthly Progress Report
	A-203	Monthly Progress Report
	A-301	Program Plan
	A-302	Quarterly Progress Report
	A-401	Monthly Weight and Balance Report

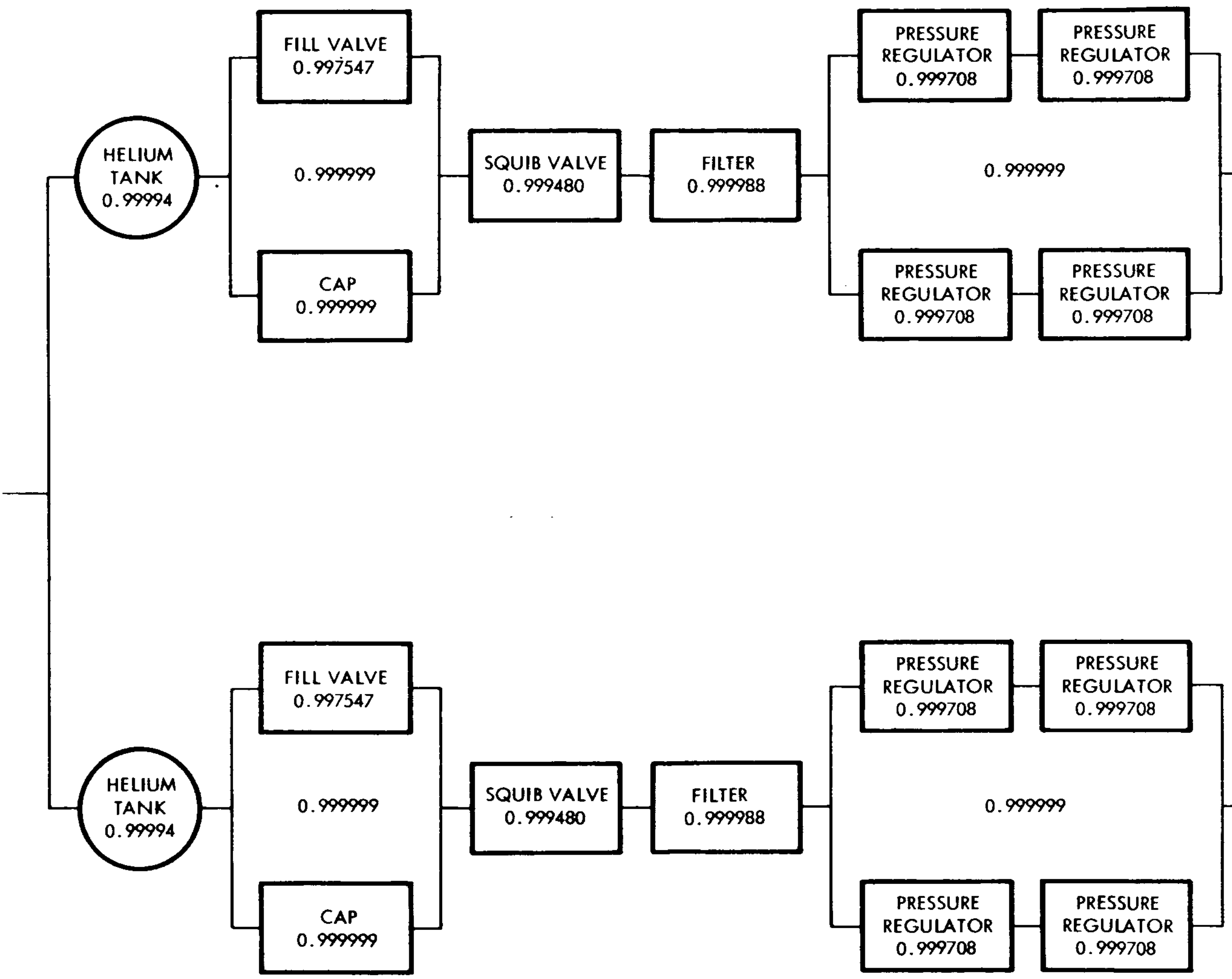
~~CONFIDENTIAL~~

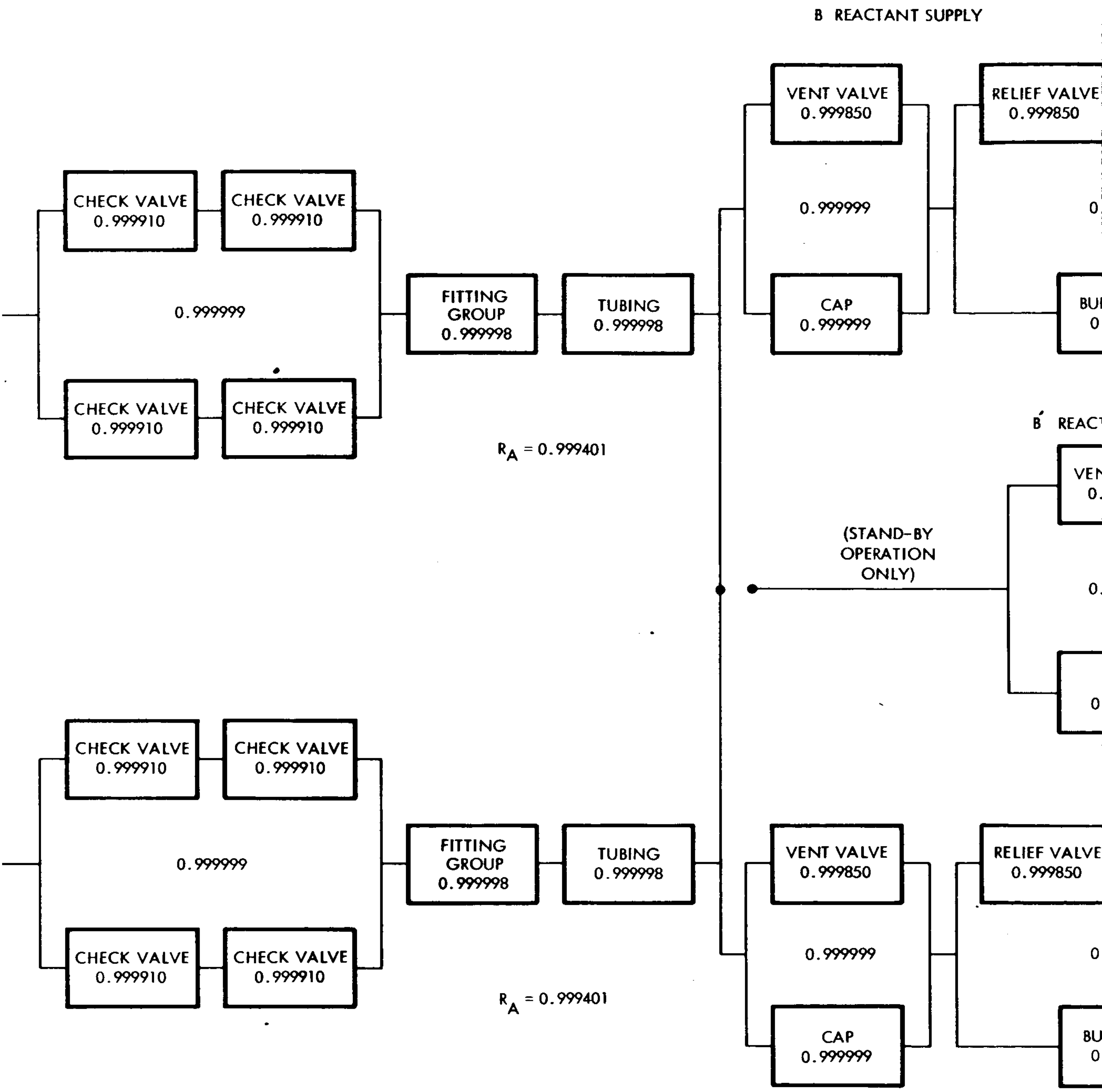
Table A-2. Subcontractor Documents Reviewed (Cont)

Source	Report No.	Title
Thiokol	A-402	Monthly Weight and Balance Report
	A-704	Drawing List
	A-705	Drawing List
	A-706	Drawing List

~~NFIDENTIAL~~

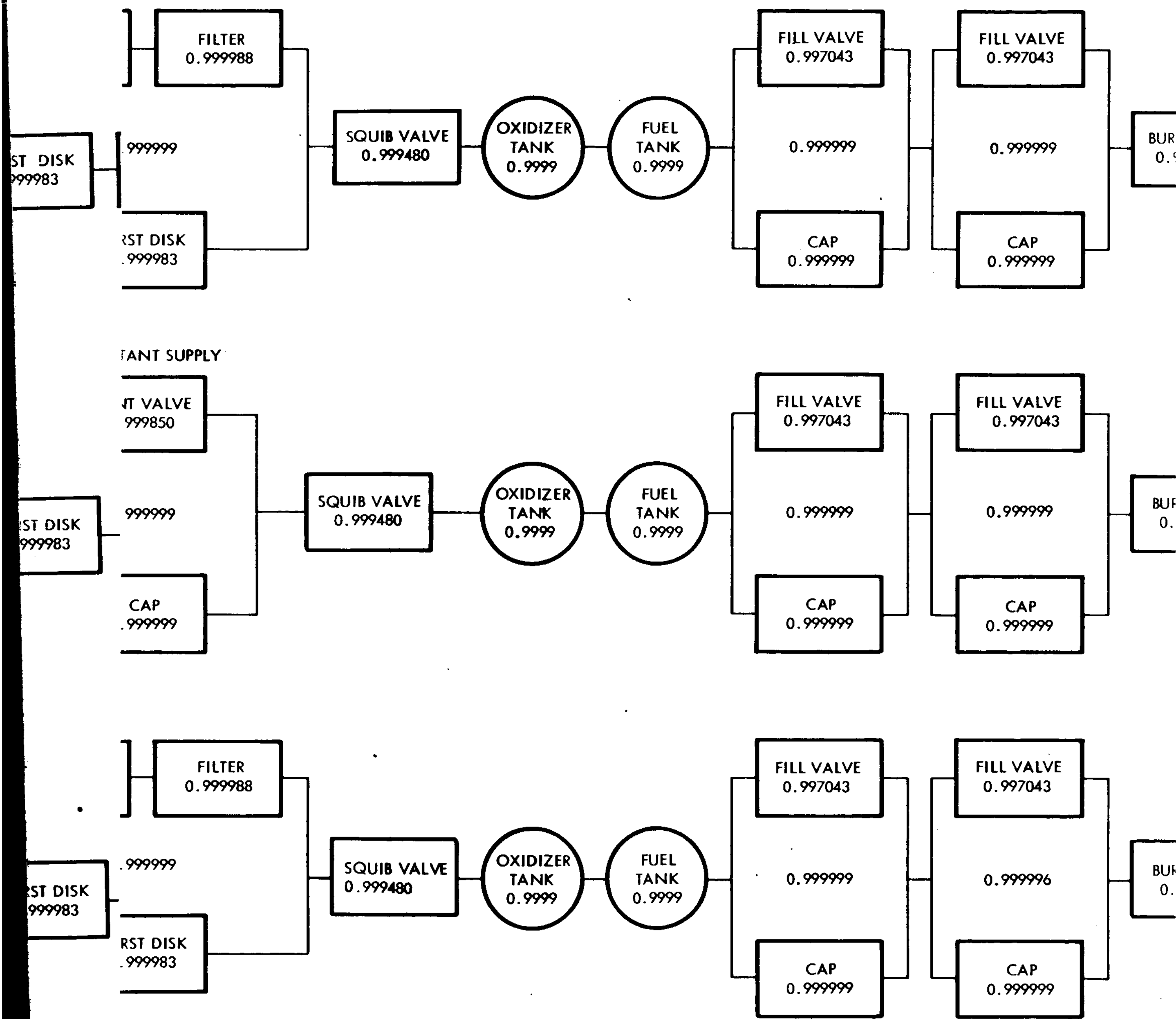
A PRESSURIZATION



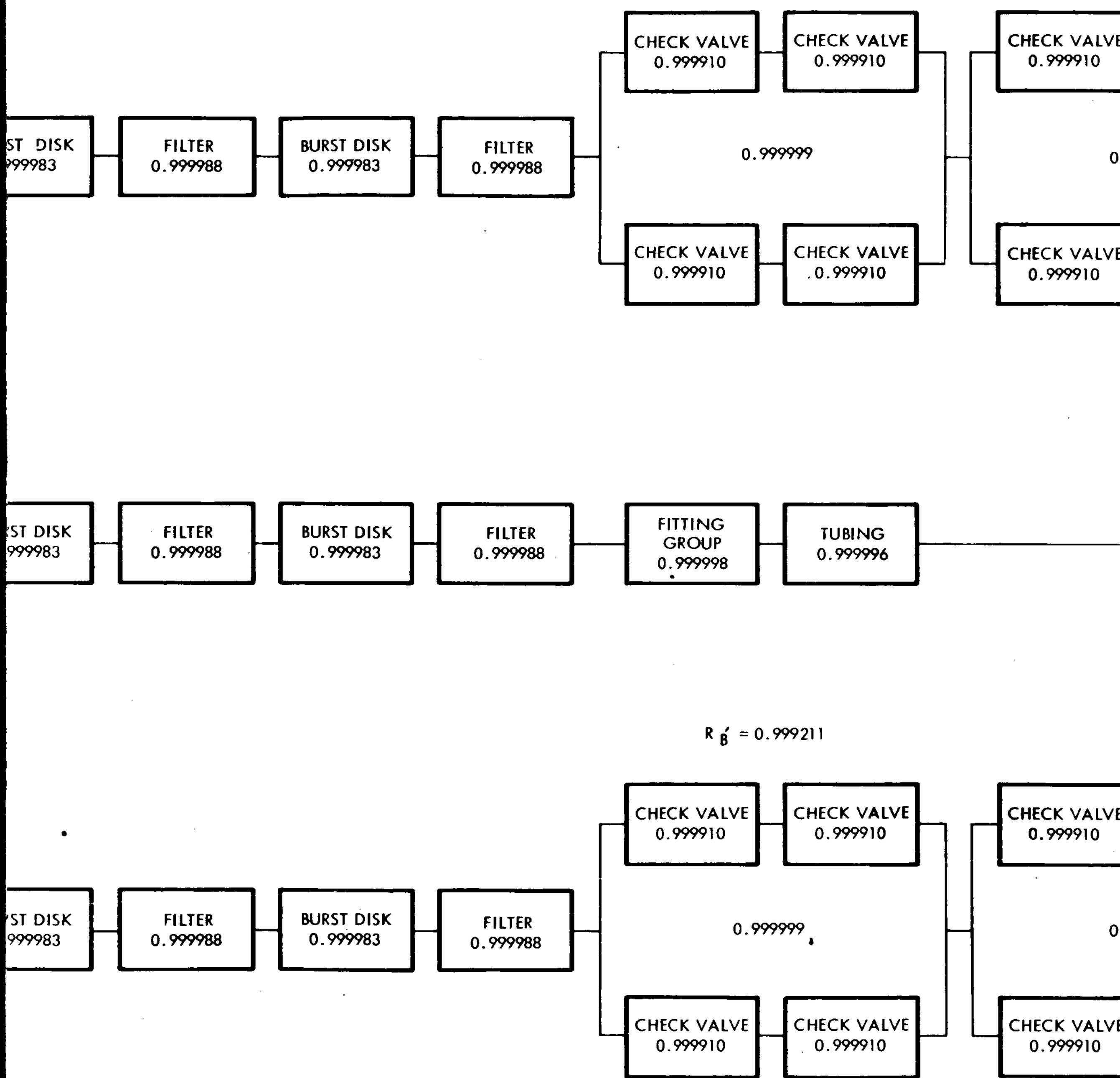


B REACTANT SUPPLY
CHECK VALVE 0.999910
CHECK VALVE 0.999910
0.999999
CHECK VALVE 0.999910
CHECK VALVE 0.999910
FITTING GROUP 0.999998
TUBING 0.999998
R_A = 0.999401
VENT VALVE 0.999850
0.999999
CAP 0.999999
RELIEF VALVE 0.999850
B' REAC
(STAND-BY OPERATION ONLY)
CHECK VALVE 0.999910
CHECK VALVE 0.999910
0.999999
CHECK VALVE 0.999910
CHECK VALVE 0.999910
FITTING GROUP 0.999998
TUBING 0.999998
R_A = 0.999401
VENT VALVE 0.999850
0.999999
CAP 0.999999
RELIEF VALVE 0.999850

2

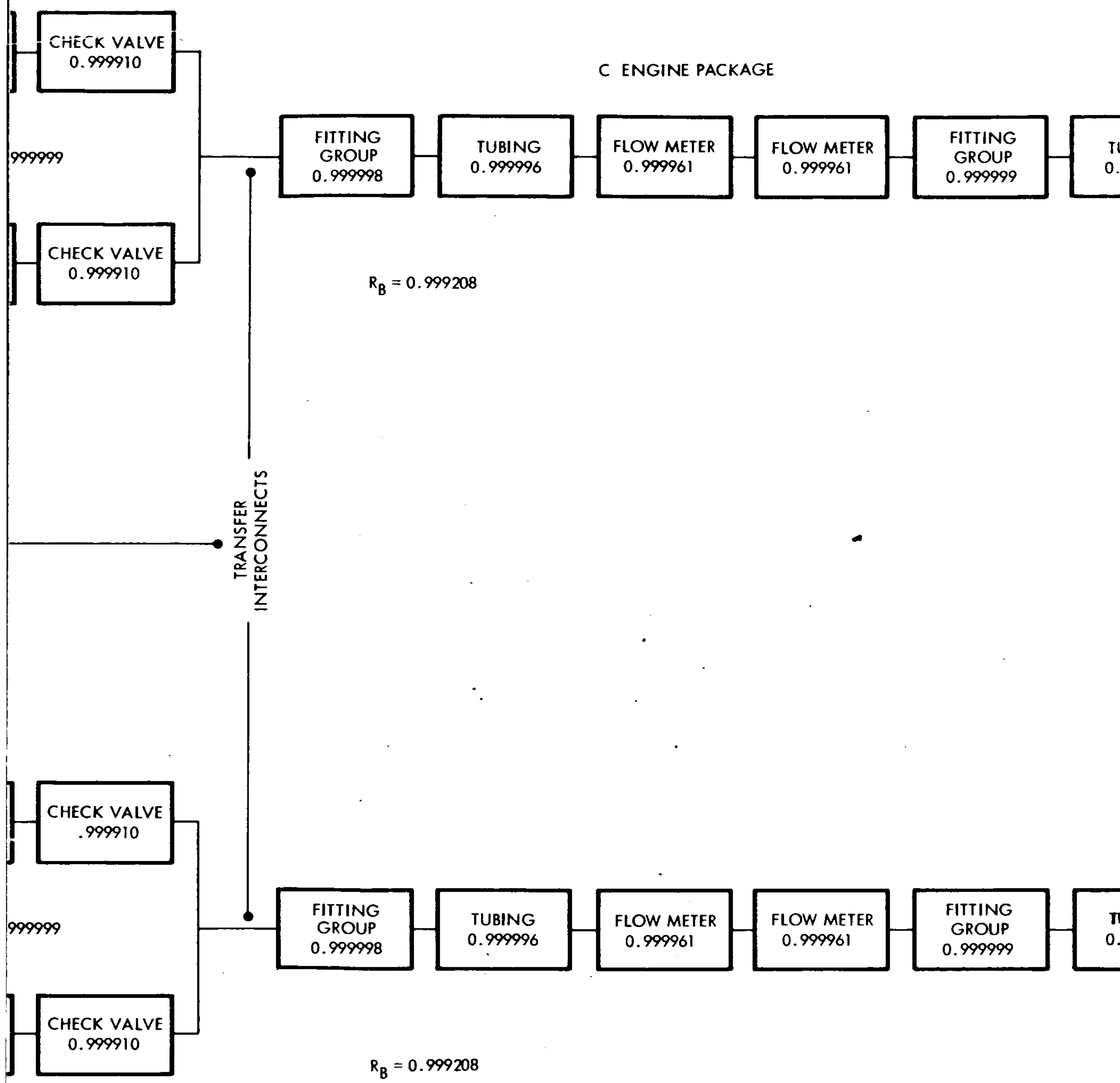


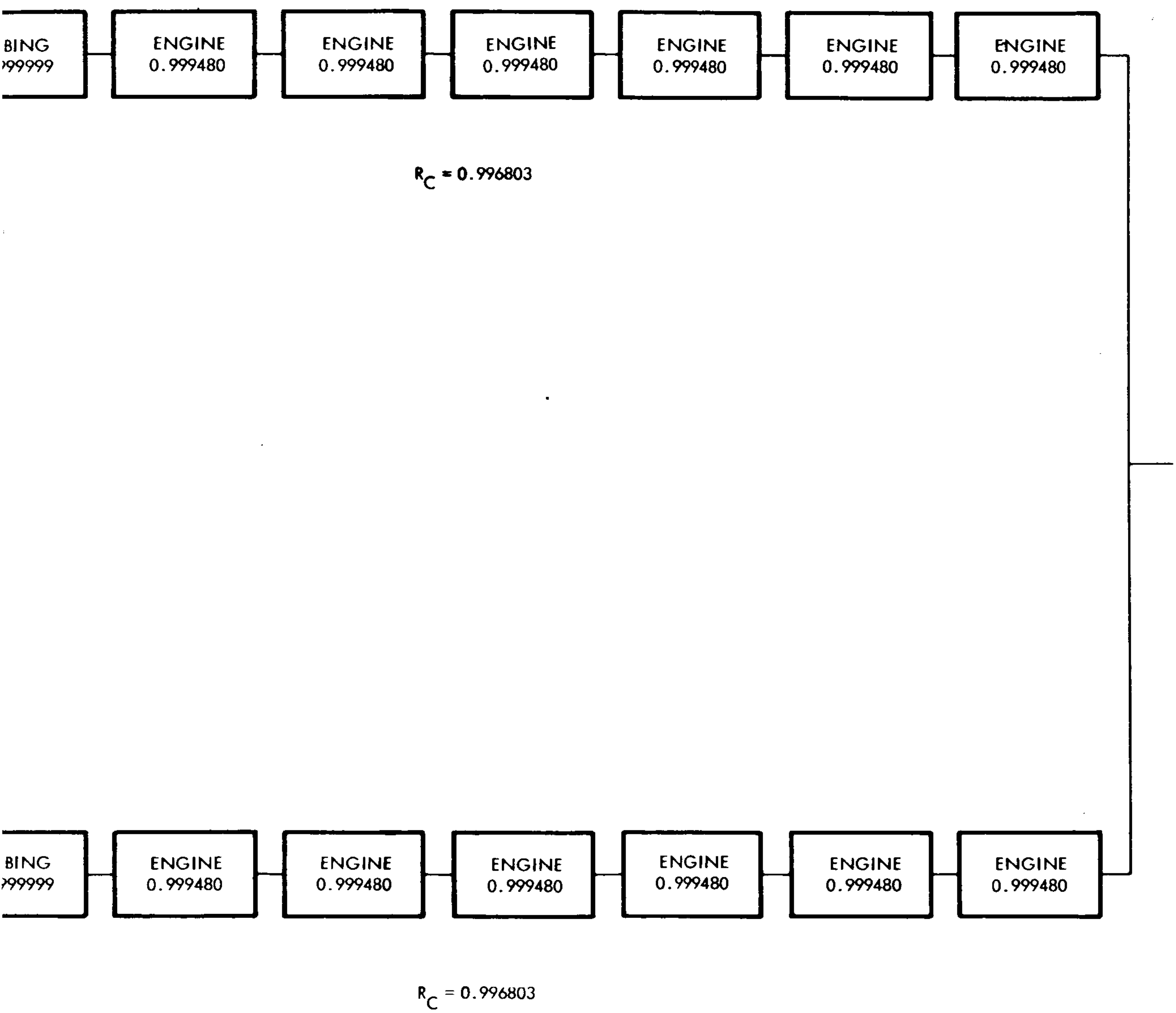
FILTER 0.999988
ST DISK .999983
.999999
RST DISK .999983
SQUIB VALVE 0.999480
OXIDIZER TANK 0.9999
FUEL TANK 0.9999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILL VALVE 0.997043
0.999999
CAP 0.999999
ANT SUPPLY
IT VALVE 999850
RST DISK 999983
999999
CAP .999999
SQUIB VALVE 0.999480
OXIDIZER TANK 0.9999
FUEL TANK 0.9999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILTER 0.999988
RST DISK 999983
.999999
RST DISK .999983
SQUIB VALVE 0.999480
OXIDIZER TANK 0.9999
FUEL TANK 0.9999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILL VALVE 0.997043
0.999996
CAP 0.999999



ST DISK
999983
FILTER
0.999988
BURST DISK
0.999983
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
ST DISK
999983
FILTER
0.999988
BURST DISK
0.999983
FILTER
0.999988
FITTING GROUP
0.999998
TUBING
0.999996
R B′ = 0.999211
ST DISK
999983
FILTER
0.999988
BURST DISK
0.999983
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910

4


CHECK VALVE
0.999910
C ENGINE PACKAGE
999999
FITTING GROUP
0.999998
TUBING
0.999996
FLOW METER
0.999961
FLOW METER
0.999961
FITTING GROUP
0.999999
CHECK VALVE
0.999910
$R_B = 0.999208$
TRANSFER INTERCONNECTS
CHECK VALVE
.999910
999999
FITTING GROUP
0.999998
TUBING
0.999996
FLOW METER
0.999961
FLOW METER
0.999961
FITTING GROUP
0.999999
CHECK VALVE
0.999910
$R_B = 0.999208$


BING
ENGINE 0.999480
ENGINE 0.999480
ENGINE 0.999480
ENGINE 0.999480
ENGINE 0.999480
ENGINE 0.999480
R_C = 0.996803
BING
ENGINE 0.999480
ENGINE 0.999480
ENGINE 0.999480
ENGINE 0.999480
ENGINE 0.999480
ENGINE 0.999480
R_C = 0.996803

6

MATHEMATICAL MODEL FOR COMMAND MODULE REACTION CONTROL SYSTEM, TRIPLE-2

$$\text{RELIABILITY} = R_A^2 \cdot R_B^2 \cdot R_C^2 + 2q_C R_B R_{B'} R_C R_{SV} R_{VO}^2 R_A^2 + 2q_A R_{VO} R_A R_{SV} R_B R_{B'} R_C^2 + 2q_B R_B R_{SV} R_{B'} R_{VO} R^2_A R_C^2 + 2q_A q_B R_{SV} R_A R_B R_{B'} R_{VO}^2 R_C^2 + 4\, q_A q_C R_A R_C R_B R_{B'} R_{SV} R_{VO}^2 + 2q_A q_B q_C R_A R_B R_C R_{B'} R_{SV} R_{VO}^2 (1 + R_{VO})$$

IN WHICH

$R_A = 0.999401$, $R_B = 0.999208$, $R_C = 0.996803$, $R_{SV} = 0.999761$, $R_{VO} = 0.999522$,

$q_A = 0.000599$, $q_B = 0.000792$, $q_C = 0.003197$,

$R_{VO}^2 = 0.999044$, and $R_{B'} = 0.999211$

$$R_{(T-2)} = (0.999401)^2 (0.999208)^2 (0.996803)^2 + 2(0.003197)(0.999208)(0.999211)(0.996803)(0.999761)(0.999522)^2 (0.999401)^2 + 2(0.000599)(0.999522)(0.999401)(0.999761)(0.999208)(0.999211)(0.996803)^2 + 2(0.000792)(0.999208)(0.999761)(0.999211)(0.999522)(0.999401)^2 (0.996803)^2 + 2(0.000599)(0.000792)(0.999761)(0.999401)(0.999208)(0.999211)(0.999522)^2 (0.996803)^2 + 4(0.000599)(0.003197)(0.999401)(0.996803)(0.999208)(0.999211)(0.999761)(0.999522)^2 + 2(0.000599)(0.000792)(0.003197)(0.999401)(0.999208)(0.996803)(0.999211)(0.999761)(0.999522)^2 (1.999522) = 0.999967$$

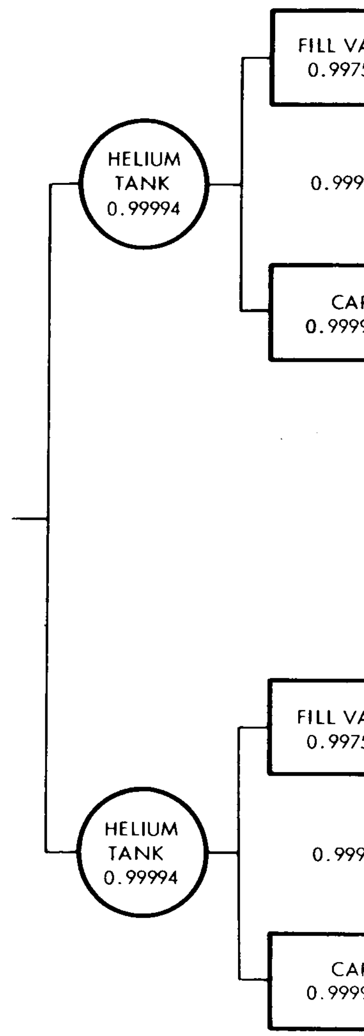
DEFINITIONS:

R_A = RELIABILITY OF HELIUM PRESSURIZATION SUBSYSTEM
R_B = RELIABILITY OF PROPELLANT SUBSYSTEM
$R_{B'}$ = RELIABILITY OF REDUNDANT PROPELLANT SUBSYSTEM
R_C = RELIABILITY OF ENGINE SUBSYSTEM
R_{VO} = RELIABILITY OF SOLENOID VALVE OPERATION - 2 VALVES
R_{SV} = RELIABILITY OF SOLENOID VALVE OPERATION ONLY
q_A = PROBABILITY OF SUBSYSTEM A FAILING
q_B = PROBABILITY OF SUBSYSTEM B FAILING
q_C = PROBABILITY OF SUBSYSTEM C FAILING

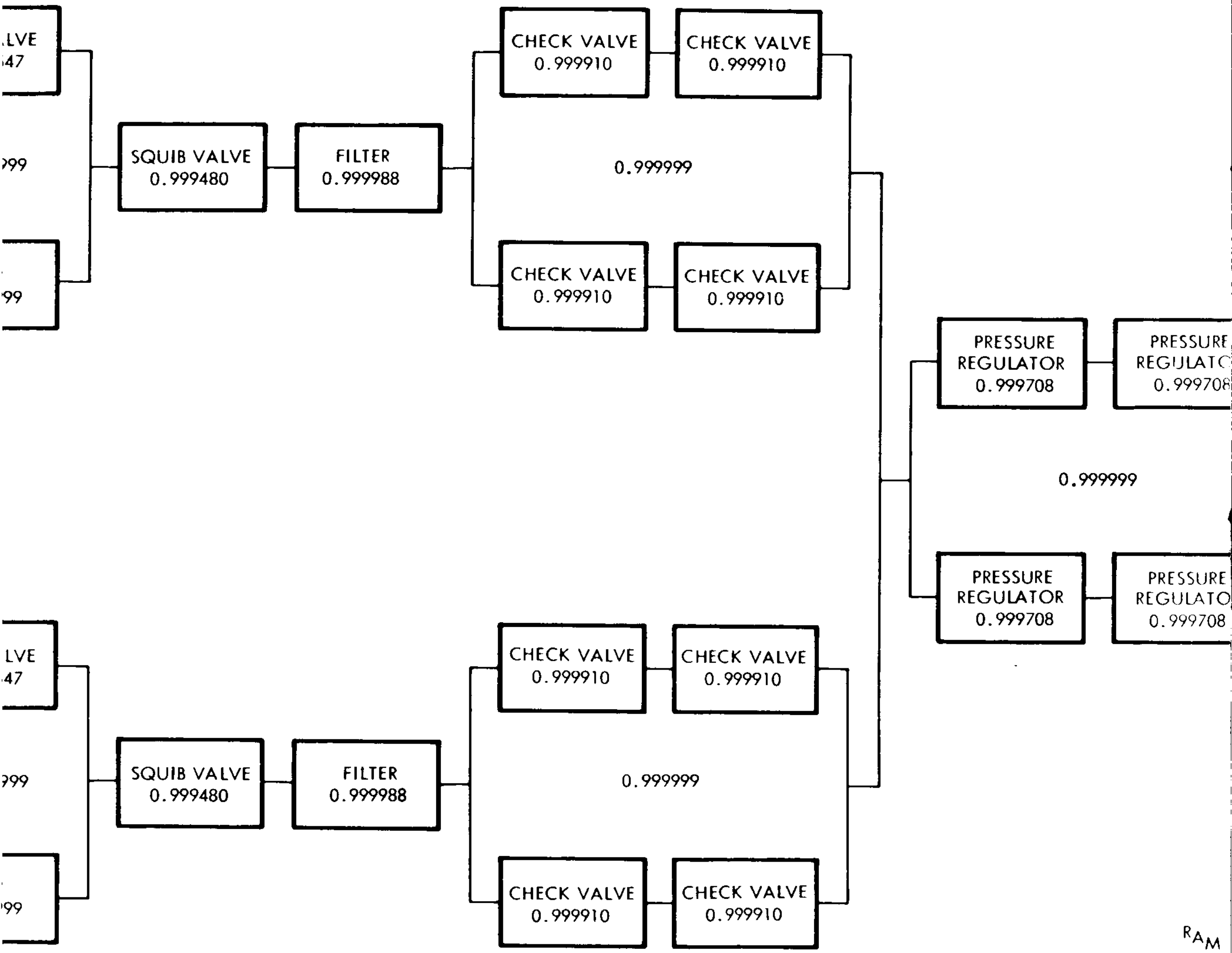
Figure 25. Command Module Triple 2 Reaction Control System Logic Network and Mathematical Model

~~CONFIDENTIAL~~

A_M PRESSURIZATI

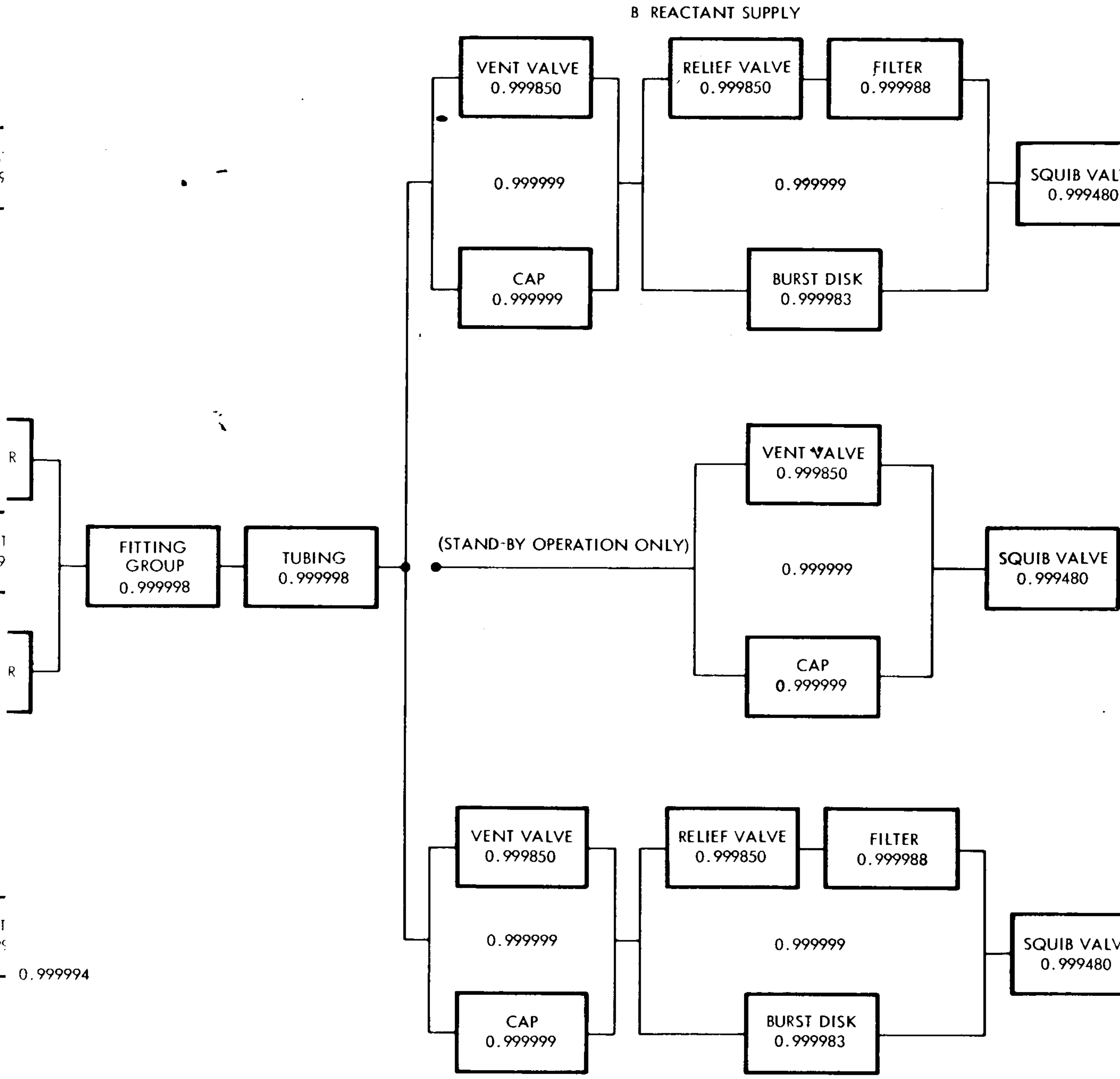


ON (MODIFIED)



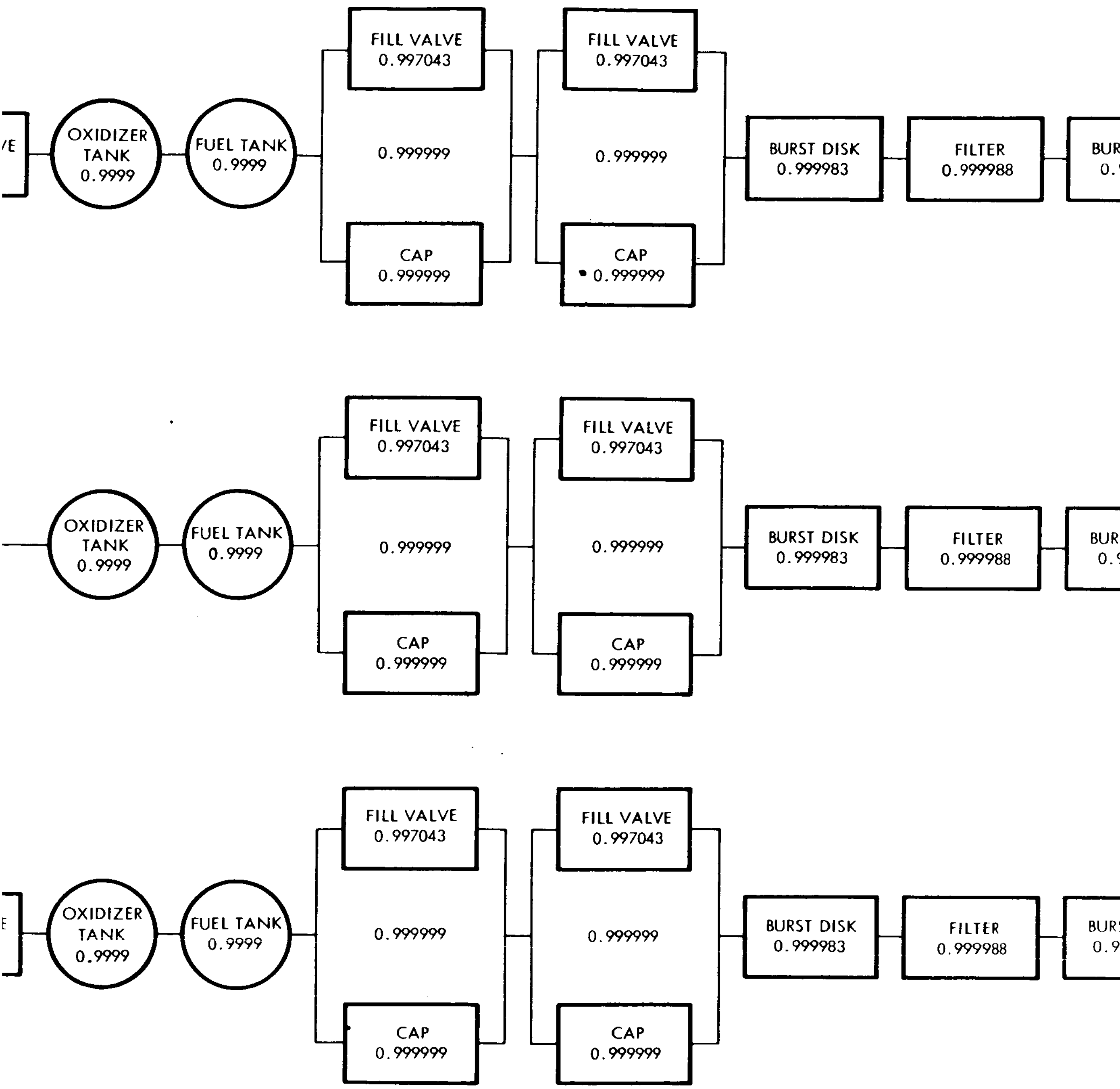
RAM

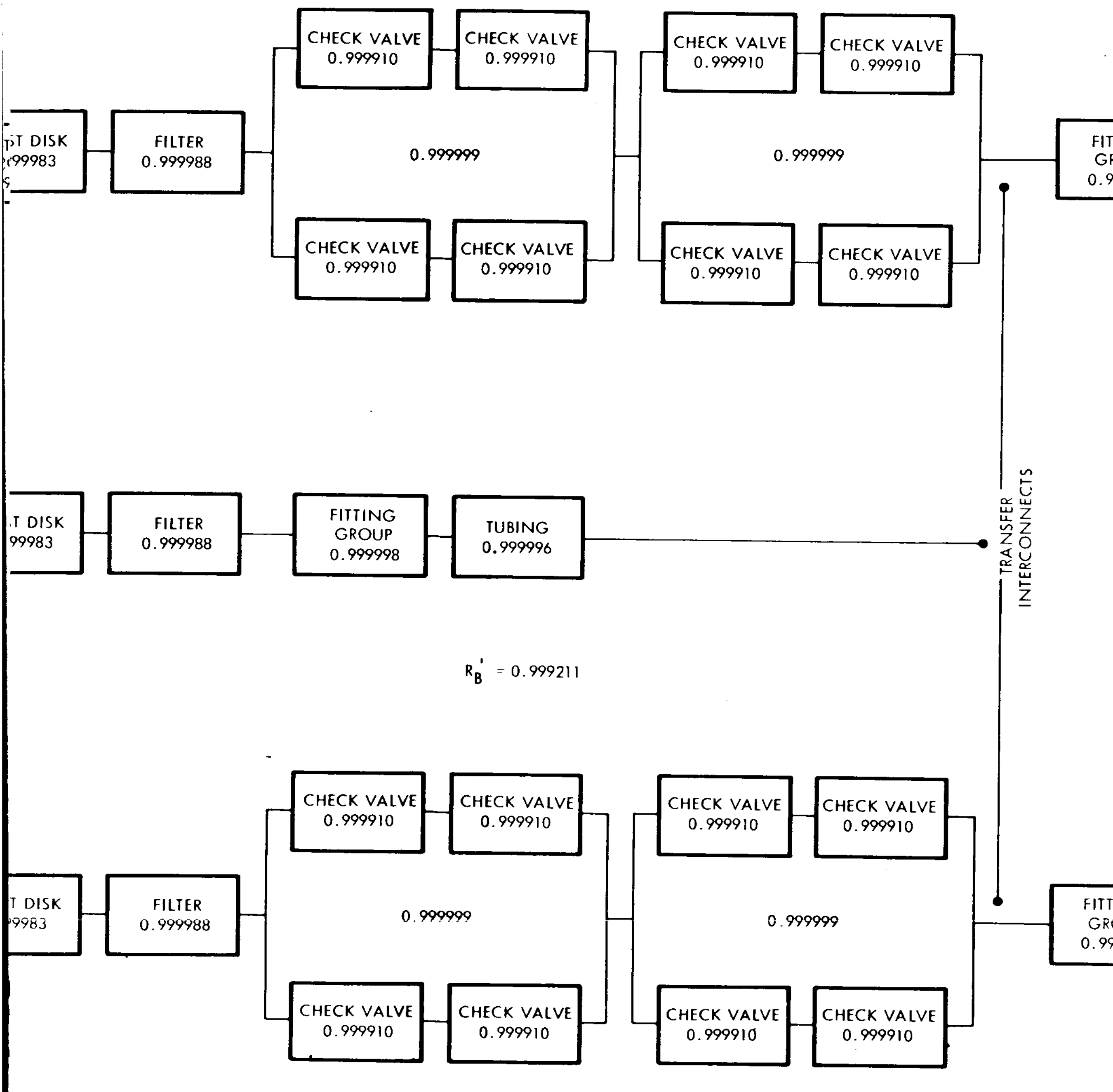
2



B REACTANT SUPPLY
VENT VALVE 0.999850
RELIEF VALVE 0.999850
FILTER 0.999988
0.999999
0.999999
SQUIB VAL 0.999480
CAP 0.999999
BURST DISK 0.999983
R
VENT VALVE 0.999850
FITTING GROUP 0.999998
TUBING 0.999998
(STAND-BY OPERATION ONLY)
0.999999
SQUIB VALVE 0.999480
R
CAP 0.999999
VENT VALVE 0.999850
RELIEF VALVE 0.999850
FILTER 0.999988
0.999994
0.999999
0.999999
SQUIB VALV 0.999480
CAP 0.999999
BURST DISK 0.999983

3

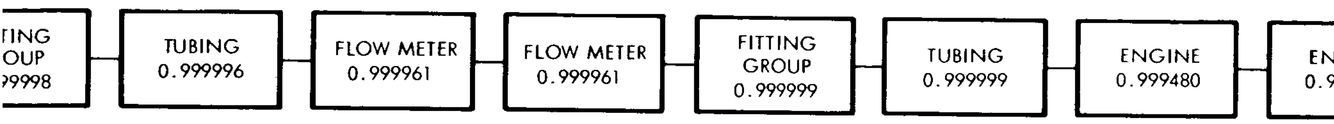

OXIDIZER TANK 0.9999
FUEL TANK 0.9999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILL VALVE 0.997043
0.999999
CAP 0.999999
BURST DISK 0.999983
FILTER 0.999988
OXIDIZER TANK 0.9999
FUEL TANK 0.9999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILL VALVE 0.997043
0.999999
CAP 0.999999
BURST DISK 0.999983
FILTER 0.999988
OXIDIZER TANK 0.9999
FUEL TANK 0.9999
FILL VALVE 0.997043
0.999999
CAP 0.999999
FILL VALVE 0.997043
0.999999
CAP 0.999999
BURST DISK 0.999983
FILTER 0.999988



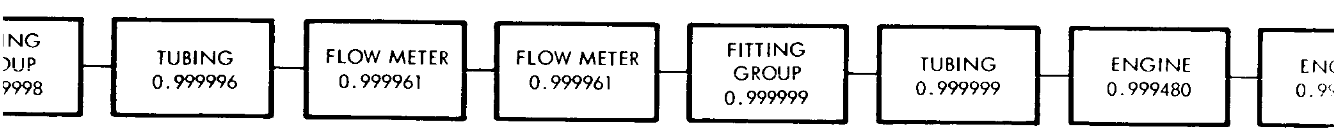
T DISK
99983
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
T DISK
99983
FILTER
0.999988
FITTING
GROUP
0.999998
TUBING
0.999996
TRANSFER
INTERCONNECTS
$R_B' = 0.999211$
T DISK
9983
FILTER
0.999988
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
CHECK VALVE
0.999910
0.999999
CHECK VALVE
0.999910
CHECK VALVE
0.999910

5

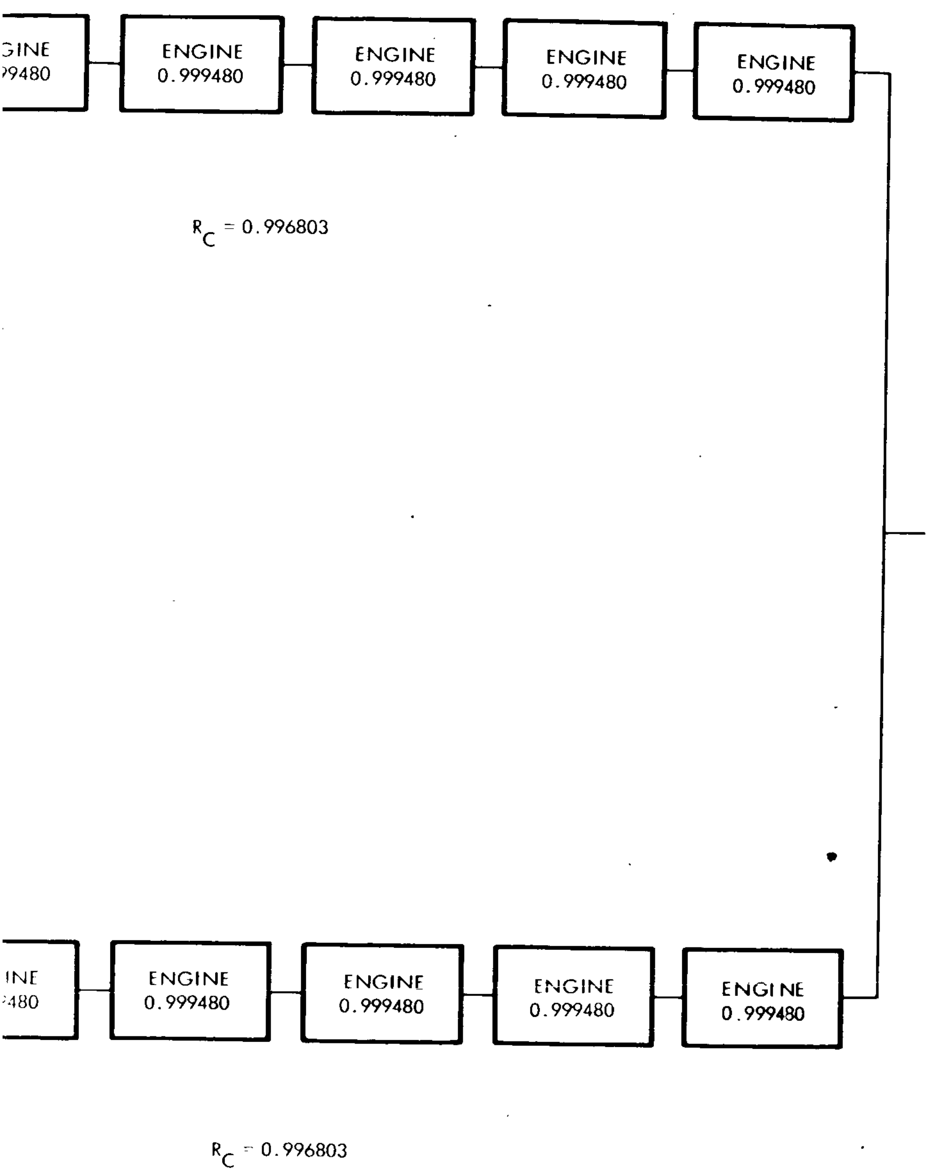
C ENGINE PACKAGE



$R_B = 0.999208$



$R_B = 0.999208$



MATHEMATICAL MODEL FO

RELIABILITY = $R_A(R_B{}^2R_C{}^2 +$

$+ 2q_Bq_CR_BR_C$

IN WHICH

R_A = 0.99999

q_A = 0.00000

R_{SV} = 0.9997

$R_{(T-3)}$ = (0.999994) [(0.999

+2(0.000792)(0.999

(0.999208)(0.99921

(0.999211)(0.99680

DEFINITIONS:

R_A = RELIABILITY

R_B = RELIABILITY

R'_B = RELIABILITY

R_C = RELIABILITY

R_{VO} = RELIABILITY

R_{SV} = RELIABILITY

q_A = PROBABILITY

q_B = PROBABILITY

q_C = PROBABILITY

Figure 26. Comman
Logic N

7

R COMMAND MODULE REACTION SYSTEM, TRIPLE -3

$2q_C R_B R_C R_B' R_{SV} R_{VO}^2 + 2q_B R_B R_B' R_{VO} R_C^2 R_{SV}^2$

$R_B' R_{VO}^2 R_{SV}^2 + 2q_C q_B R_B R_B R_B' R_C R_{VO}^3 R_{SV}^2)$

4, $R_B = 0.999208$, $R_B' = 0.999211$, $R_C = 0.996803$,

6, $q_B = 0.000792$, $q_C = 0.003197$,

61, and $R_{VO} = 0.999522$

$208)^2(0.999208)^2 + 2(0.003197)(0.999208)(0.996803)(0.999211)(0.999761)(0.999522)^2$

$208)(0.999211)(0.999522)(0.996803)^2(0.999761)^2 + 2(0.000792)(0.003197)$

$1)(0.999522)^2(0.999761)^2 + 2(0.003197)(0.000792)(0.999208)$

$3)(0.999522)^3(0.999761)^2 \Big] = 0.999973$

OF HELIUM PRESSURIZATION SUBSYSTEM
OF PROPELLANT SUBSYSTEM
OF REDUNDANT PROPELLANT SUBSYSTEM
OF ENGINE SUBSYSTEM
OF SOLENOID VALVE OPERATION - 2 VALVES
OF SOLENOID VALVE OPERATION ONLY
OF SUBSYSTEM A FAILING
OF SUBSYSTEM B FAILING
OF SUBSYSTEM C FAILING

d Module Triple 3 Reaction Control System
twork and Mathematical Model

8

[redacted]